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FACULTY OF ELECTRICAL ENGINEERING, COMPUTER SCIENCE AND INFORMATION TECHNOLOGY OSIJEK

Undergraduate study

PERFORMANCE ANALYSIS OF A MICROGRID WITH RENEWABLE ENERGY SOURCES

Bachelor's degree final paper

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1. Introduction

In a world that tends to collapse, finding new and more efficient ways to take advantage of renewable energy sources may be the key to changing that trend and redirecting it towards a more sustainable future. To do so, a paradigm change must be done; the microgrids powered by renewable energy have to take over.

Following the European Union energy policies in these last years, and with the increasing electricity demand and dependence from it, distributed generation based on renewable energy sources can be the alternative to the traditional centralized and non-renewable energy production model.

They may also be vital to accomplish the EU objectives known as the three twenties 20-20-20; which tries to achieve a 20% of power generation coming from renewable energy sources, greenhouse gases emissions 20% lower than the 1990 levels, and 20% increase in energy efficiency in all the EU countries before 2020.

1.1. Main goal of the paper

The main goal of this paper is to compare different types of equipment, depending on the price, in two case studies: on-grid microgrid and isolated microgrid. To do so, an electrical performance and cost-benefit analysis using HomerPro will be conducted. The objective is to see if these types of microgrids are viable both economically and technically.

1.2. Economic concepts

In a society where the importance of a project is determined by its economic viability, is important to define first some economic concepts that will be important in this project, the Levelized Cost of Energy, the Net Present Cost and the discounted payback period.

The Levelized Cost of Energy (LCOE), according to [1, pp. 34], is a method to compare different types of energy sources and technologies over the lifetime of the projects, considering also how the passing of time can affect the prices of maintenance and fuel, as well as the possibility of a major breakdown of the plant. LCOE is calculated as in (1-1).

$$LCOE = \left[\frac{R \cdot c_p}{H \cdot f}\right] + \left[l \cdot \left(\frac{c_o}{H \cdot f}\right)\right] + \left[l \cdot \left(\frac{c_f}{H \cdot f}\right)\right] \quad (1\text{-}1)$$

As we see in the formula, the LCOE it is based on its initial investment (cost of the plant: c_p), the operation and maintenance costs (c_o) and the fuel costs (c_f). It also takes into account the capacity factor (f), the hours per year that the plant is functioning (H), the capital recovery factor (R) and the levelization factor (l).

The Net Present Cost (NPC) of a component is the present value of the installation, operation and maintenance of that component, minus the present value of the profit generated by it, over its lifetime.

The discounted payback period is a method used to determine how profitable is a project, reflecting the amount of time necessary to recover the initial investment taking into account the different cash flows for every period.

2. Microgrids

Nowadays, production of energy is based on big, centralized power plants fueled by non-renewable primary energy, such as coal, petroleum or natural gas. These electricity-producing power plants normally use synchronous generators and turbines; moreover, they are usually far away from the loads and consumers of the energy they are producing, making the transmission and distribution lines to be long.

These facts of the traditional large energy producing systems generate a series of problems, which can be divided in three levels:

- Generation: Inefficient generating systems, very high renewal costs when obsolete or broken, emission of gases that contribute to greenhouse effect and other pollution due to combustion of fossil fuels, nuclear waste and possibility of reactor failure, etcetera.
- Transport: Transient and dynamic instability due to consumption, voltage instability due to reactive loads, thermal limit to transmitted power, possibility of failure by natural elements or other accidents in long transmission lines, etcetera.
- Distribution: Necessity of power transformation stations, non-linear loads, possibility of failure due to natural elements or other accidents, etcetera.

The scheme of the typical electric network is shown in Figure 2.1

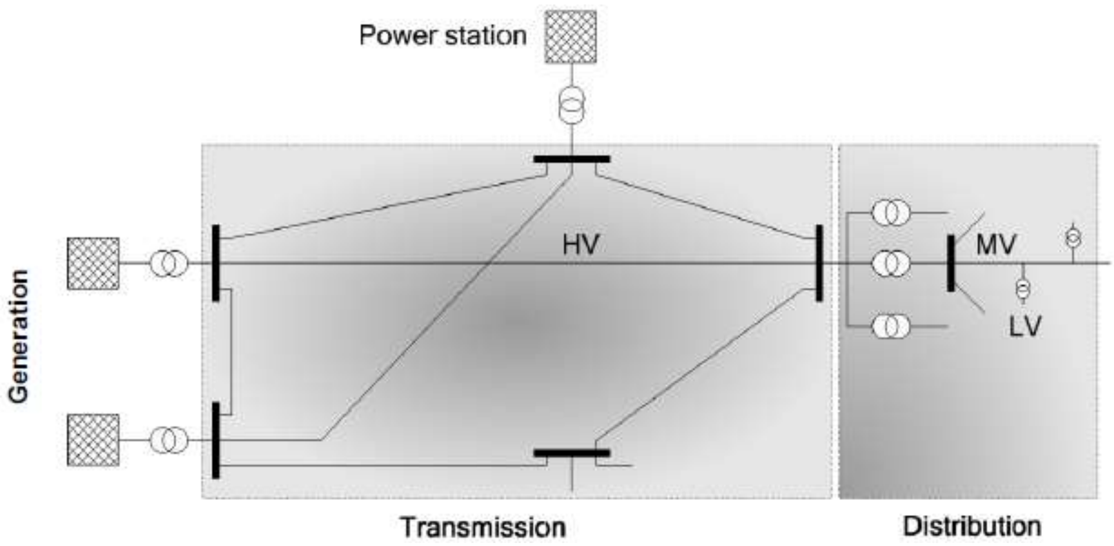

Figure 2.1. *Simplified one-line diagram of the actual electrical network, source [2]*

These problems can be minimized at the same time as we maintain or even improve the capabilities of the network by changing the paradigm of centralized energy production and introducing microgrids to the system.

A microgrid, as defined by the U.S. Department of Energy [3], is a “group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode”. Professor Robert H. Lasseter first used “microgrid” in 1998 referred to it as a combination of three key elements: DG (Distributed Generation) + PFC (Power Flow Control) + ESS (Energy Storage Systems). In Figure 2.2 is depicted the typical elements of a microgrid.

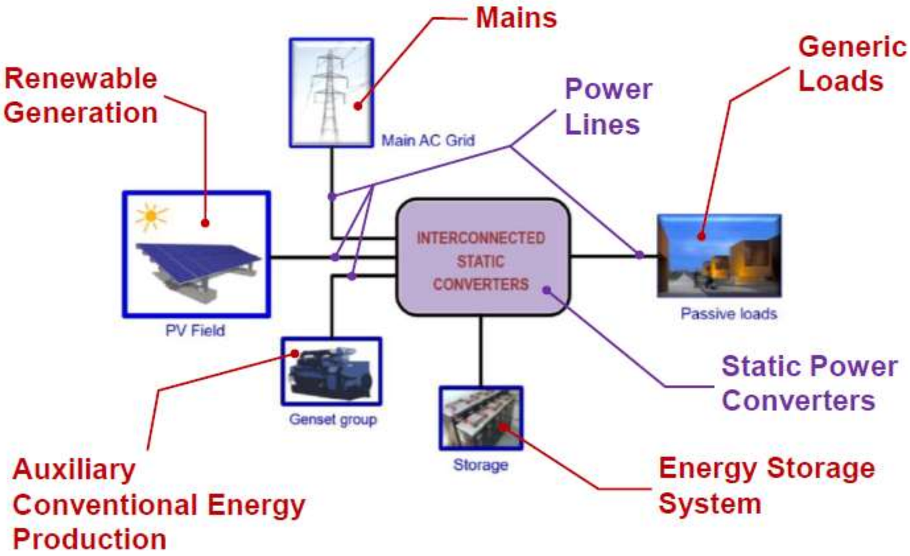

Figure 2.2. *Typical elements of the microgrid, source [4]*

As we see in Figure 2.2., and taking it as an example of a typical microgrid connected to the main grid, we distinguish between the distributed generation (photovoltaic panels and auxiliary genset group), the energy storage system (the batteries) and the power flow control (the interconnected converters).

This microgrid distribution brings a series of advantages for the system:

- Bust the usage of renewable energy sources, contributing to the fight against climate change and thus helping the environment.
- Improves the resiliency and power quality of the network, making it more reliable.

- Has the capacity to operate (some of them, mostly microgrids connected to main grid, only for a certain time if they don't have an appropriate) without the electricity supply of the main grid, making them suitable for emergency operations while blackouts.
- Enables the participation in new markets for demand response and auxiliary services.
- Optimization of the usage of energy.

However, not everything is good about microgrids, as they are facing some problems also, namely:

- The price of some components of the microgrid can be too expensive for most of the population.
- Large differences between load and production for intermittent renewable sources such as solar panels and wind generators.
- Durability of the components
- Protection
- Legal and regulatory problems in some countries

3. PV panels theory

3.1. The solar resource

Most of the energy we are using today comes from the Sun; even fossil fuels obtained their energy from it in the past. The Sun is the star on our planetary system and releases a huge amount of energy because of its nuclear fusion where hydrogen is converted into helium. From all this energy, around $5.6 \cdot 10^{24} J$ arrives to the atmosphere of our planet [5], where the 31% of it is reflected. The rest enters the atmosphere, and apart from the atmosphere absorbing a small amount of it, reaches the surface where an average of 4.2% is reflected back into the atmosphere.

In a particular spot, the sum of the direct radiation arriving from the Sun and the diffuse radiation is the global radiation (G_g), in Figure 3.1 is shown a map of the amount of global irradiation arriving to Croatia.

Figure 3.1. *Global horizontal irradiation in Croatia, source [6]*

This solar resource can be exploited using three methods:

- Passive solar energy: Using architecture to take advantage of the Sun and its benefits in the buildings (for example with an efficient placement of the windows). It is the simplest way to use the solar resource.

- Thermal solar energy: Converts the solar irradiation in heat, being able to use this heat afterwards for buildings' hot water or heating system.
- Photovoltaic solar energy: Converts the solar radiation in electricity through solar cells. We will be deepening this one in this project.

3.2. Functioning of the PV panels

The photovoltaic solar panels are made up of a transparent top sheet with an anti-reflective layer and a lower enclosure. In between, we can find the electric connexions and the converter substrate. Figure 3.2 shows the typical structure of a solar cell and its equivalent circuit diagram.

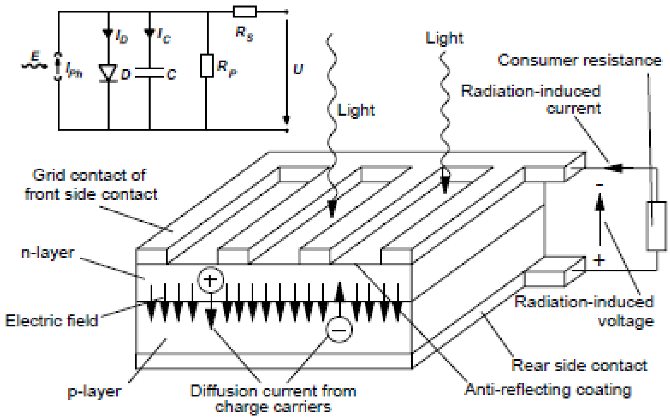

Figure 3.2. *Structure of a typical solar cell [5]*

The photovoltaic effect converts the electromagnetic radiation of the light into electricity. When the photons make contact with a semiconductor (such as silicon), they transfer their energy to electrons from the valance band, causing excitation on them, enabling these free electrons to cross the junction, and thus creating a current, because one side of the junction will have a positive charge and the other will have a negative charge. This current created by the photovoltaic effect can be used to power an electric circuit.

The current created by the photovoltaic panels is direct current. It can be directly used if we want to power a device that needs DC to function or if we want to store it in batteries. However, it can be transformed into AC using an inverter and, this way, use it to give current to a load that needs AC or to be sold into the main grid, with the subsequent subventions.

The electrical characteristics of the PV panels can vary depending on the receiving irradiation and the temperature of the panel. In Figures 3.3 and 3.4, the effects of the irradiation and temperature are shown.

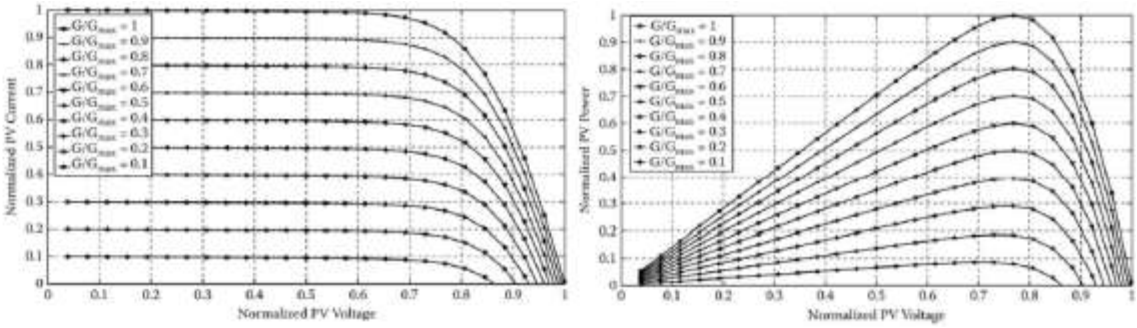

Figure 3.3. *Effect of irradiation on the Current vs Voltage and Power vs Voltage characteristics of a PV panel, source [7]*

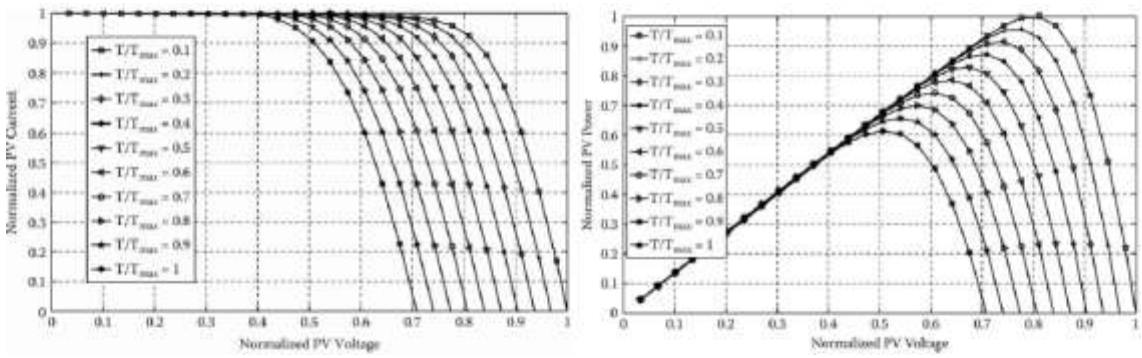

Figure 3.4. *Effect of temperature on the Current vs Voltage and Power vs Voltage characteristics of a PV panel, source [7]*

Photovoltaic panels can be divided in different types:

- Monocrystalline silicon panels: The most effective of the typical photovoltaic panels, in laboratory conditions they can reach a 24% efficiency, although in real conditions its efficiency is around 15%. It is obtained from pure melted silicon and doped with boron; the crystal then is cut in hexagonal shape. The process of manufacturing these panels is complicated and expensive, resulting in higher prices, but they last longer than other panels and work better with low light conditions.
- Polycrystalline silicon panels: Their efficiency is around 13%. The process of fabrication is similar to the monocrystalline, but with less number of phases of crystallization, resulting in its characteristic color with a mixture of different shades of blue. It’s less expensive than the monocrystalline, but they suffer more at high temperatures and last less.

- Amorphous panels: The less efficient option, with a conversion rate of less than 10%. In addition, its power degrades over time. The process of fabrication is quite easy, laying it as a sheet in a substrate such as glass or plastic. For all this, it is the cheapest option.
- Other types of panels: Apart from the three types of cells we mentioned above, which are the most common ones, we can find a series of other types of panels such as the ones formed by hybrid cells, where two different types of PV technologies are combined, making them more efficient but also more expensive. Moreover, we can find cells that do not use silicon for its fabrication, such as organic photovoltaic panels, CIGS (Copper Indium Gallium Selenide) or the cadmium-telluride cells.

In Figure 3.5 is shown the evolution of the efficiency for different types of solar panels through time.

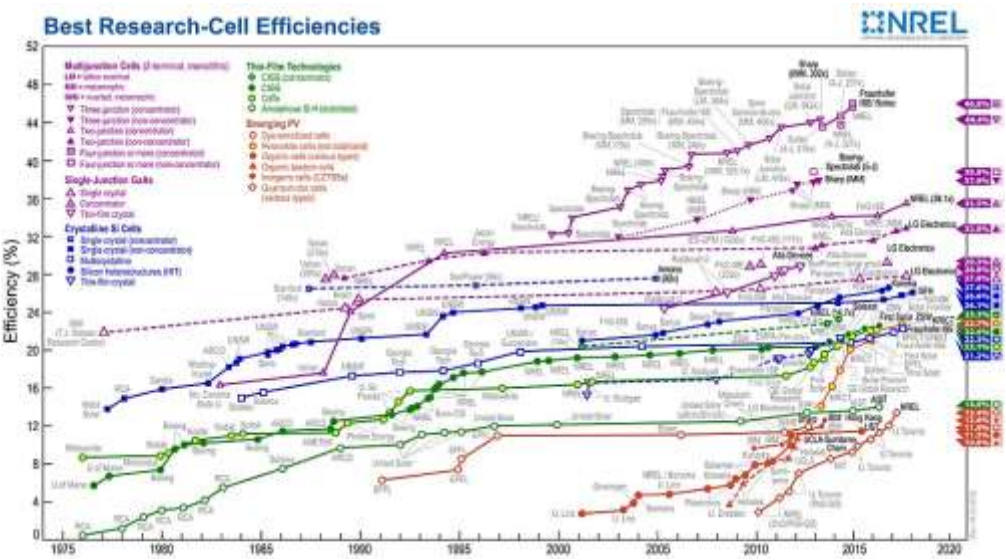

Figure 3.5. *Different types of solar cells energy conversion efficiency through time [8]*

This kind of technology has a series of advantages and disadvantages. As advantages, we have:

- High durability and reliability
- No usage of fossil or any other kind of fuels
- Enhance independence of the grid/system
- Low maintenance cost
- Distributed generation

As disadvantages, we have:

- High price

- Dependence on the weather, no functioning at night
- Necessity of a storage system if working in an isolated microgrid
- Low efficiency
- Occupies a lot of space

4. Batteries theory

The storage system is a key element in an islanded microgrid: renewable power sources that have a high dependence on meteorological conditions such as solar panels or wind generators require an efficient storage system due to their generation intermittence. Storage systems are the main limiting factor for the general adoption of renewable generation and development of these storage systems is critical to satisfy the increasing demand of electrical energy.

Batteries are the most common technologies used as storage systems. Based on electrochemical reactions, batteries store energy in chemical reagents capable of generating charges. Batteries can be used to reduce electricity costs, storing electricity obtained at off-peak times when its price is lower, and using the stored electricity at peak times. Moreover, batteries maintain and improve power quality, frequency and voltage of the grids or microgrids. Finally, in microgrids they can be used to improve the reliability of the power supply, supporting users when power network failures occur.

Apart from being used for grid or microgrid applications, batteries are also of common use for starting engines, lightning, portable devices, electric tools, and, lately, they have received a lot of attention and research due to its potential as energy source for electrical vehicles.

A battery contains one or more electrochemical cells. The anode is the negative electrode from which electrons are generated to carry out whatever task they are required to; the cathode is the positive electrode to which the positive ions migrate inside the cell while the electrons migrate through the external electrical circuit (only electrons flow is allowed in this external circuit). The electrolyte is commonly a liquid solution that contains a salt dissolved in a solvent, stable within the presence of both electrodes and that allows the flow of ions.

The parameters that define a battery are the voltage (*V*), the capacity (*Ah*), the power density (W/m^3), life cycles, self-discharge and discharge depth.

The battery people decide to use will depend on its purpose. If the intention is saving money by load and peak levelling, the batteries have to have a high power density and discharge depth, and be able to recharge at high rates for several cycles. Otherwise, if the intention is a seasonal energy storage, the battery should have a high capacity, a low self-discharge rate, and be able to operate during a large amount of low-depth cycles.

There are different types of batteries, depending on the reagents. The most common ones are:

- Nickel-Metal Hydride (NiMH): The nickel metal hydride batteries are rechargeable and they are kind of the evolution of the nickel-cadmium batteries. They both use nickel oxide hydroxide but the negative electrodes use a composite metal instead of cadmium. The self-discharge rate is somewhat high (around 0.5-4% at room temperature)
- Ion-Lithium (LiIon): The LiIon batteries have a similar appearance to the rest of the batteries, a metallic container with cylindrical shape. Normally, the positive electrode is cobalt oxide and lithium, and the negative electrode is graphite. They have a bigger energy density than the Ni-Metal batteries, a better autodischarge shorter charge periods and a better discharge voltage. However, they need some security measures to prevent harm from high temperatures (one of the biggest problems of these batteries is overheating) and pressure, and that makes these kind of batteries more expensive than the Ni-Metal batteries.
- Sodium Sulphide (NaS): The sodium works as the active material in the negative electrode and the β-Al_2O_3 is the electrolyte. These batteries have a cylindrical shape and a considerable height, because the bigger they are, the more efficient. The cells have to operate at high temperatures (between $270ºC$ and $350ºC$) to maintain the materials in the electrodes active in a molten state. This is one of the main disadvantages; due to security problems, these batteries need a caring thermal management. On the other hand, its life cycle is long and has a low cost potential compared to other advanced batteries.
- Lead-Acid: Lead-Acid batteries are a relatively low cost choice. They are reliable and robust, with a wild range of different capacities available. The composition of these batteries consists in a lead-dioxide cathode, a lead alloy anode and sulphuric acid as electrolyte. They can deliver high currents; however, they have a relatively low life cycle, and a low energy-volume ratio.

5. Inverters theory

Inverters are necessary if we want to convert the direct current generated by our photovoltaic panels into alternate current to be used by the home appliances or to be sold to the grid. However, the batteries also need DC current, so we will be using a device that not only converts current from AC to DC but also can decide and manage when to deviate the energy flow to the batteries, to the load or to the grid (if there is any).
The basic functioning of inverters is explained by the usage of semiconductor power devices to obtain a square signal that, afterwards, become a sinusoidal signal by using power filters. The total harmonic distortion (THD) allows us to know the quality of an inverter, because the less harmonics we have in the output signal the better the inverter and the filters acting in it.

The characteristic parameters that define an inverter are:

- Nominal Power: The power that the inverter can supply.

- Nominal Tension: The voltage to be applied to the input terminals of the inverter.

- Efficiency: The ratio, expressed as a percentage, between the powers present at the exit and at the entrance of the inverter.

- Waveform: At the output terminals of the inverter, an alternating signal appears, characterized mainly by its waveform and its effective voltage and frequency values.

There are different types of photovoltaic inverters, and they can be classified following different criteria. According to the number of phases we can find monophasic and three-phase inverters, with regard to the configuration of the system, we can distinguish between central inverters, chain inverters (string) and modular inverters (AC modules). In addition, with respect to the number of stages, they can be distributed among the inverters of one stage, two stages and multistage. They can also be classified according to its waveform:

- Square wave: Typical from low power economic inverters, suitable for purely resistive devices, such as lighting elements and others.

- Modulated square wave: Also characteristic of low power inverters, but with a spectrum of possible elements of consumption wider than the previous type, which includes lighting, small motors and electronic equipment not very sensitive to the power signal.

- Pure sine wave: This type of inverters provides a waveform to its output that, for practical purposes, can be considered identical to that of the general electrical network, thus allowing the power supply of any consumer device or, where appropriate, the connection to the network.

- Modified sine wave (or trapezoidal): Intermediate between the two previous ones, allows to expand the spectrum of consumption and power elements, limited in the modulated square wave.

6. Study Case Microgrid

We will be conducting two case studies, one of them with our microgrid working in isolated mode, and the other one working connected to the main grid. We will be using the program HOMER Pro. In this program, specialized in microgrid analysis, we can find all the tools we need to perform the studies we want. Moreover, this program counts in its database with all the equipment necessary to create a microgrid.

First, all the simulations and case studies will be conducted during a project lifetime of 25 years, and taking into account a discount rate of 8%, an inflation rate of 2% and a 0% annual capacity shortage.

The location will be the one from the Faculty of Electrical Engineering in Osijek, as shown in Figure 6.1:

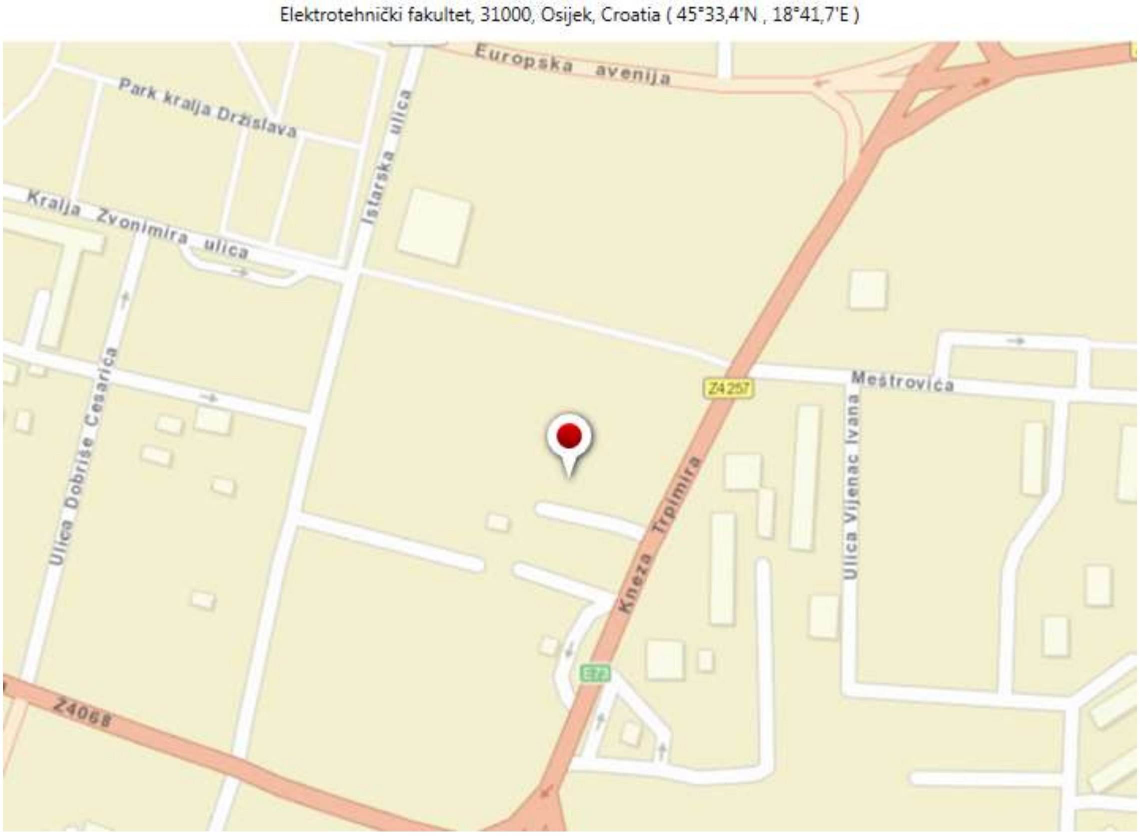

Figure 6.1. *Location of the project.*

All the environmental data (temperature, irradiation, clouds, hours of sun, etcetera) is taken automatically from the HOMER software for this location.

In every one of our two case studies, we will simulate our microgrid performance for three different types of equipment depending on the price. The inverter will be the same in all case studies, and so will the load. However, apart from having the main grid in the first case study and not in the second, we will perform the analysis with the following equipment:

- Load: A prototypical house provided by HOMER Pro, will have these characteristics:

An average energy consumption of 11.27 *kWh/day* and an average power consumption of 0.47 *kW*, with a peak of consumption of 2.81 *kW* and a load factor of 0.17. The load will use Alternate Current. The peak month will be July, and the average load (*kW*) per hour of every month will be:

In Table 6.1 is shown the average load per hour on Weekdays:

Table 6.1. *Average load (kW) per hour on weekdays.*

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0.087	0.09	0.098	0.109	0.12	0.128	0.131	0.128	0.12	0.109	0.098	0.09
1	0.076	0.079	0.085	0.095	0.105	0.111	0.114	0.111	0.105	0.095	0.085	0.079
2	0.076	0.079	0.085	0.095	0.105	0.111	0.114	0.111	0.105	0.095	0.085	0.079
3	0.076	0.079	0.085	0.095	0.105	0.111	0.114	0.111	0.105	0.095	0.085	0.079
4	0.262	0.271	0.294	0.327	0.36	0.383	0.392	0.383	0.36	0.327	0.294	0.271
5	0.4	0.415	0.45	0.5	0.55	0.585	0.6	0.585	0.55	0.5	0.45	0.415
6	0.44	0.457	0.495	0.55	0.605	0.644	0.66	0.644	0.605	0.55	0.495	0.457
7	0.4	0.415	0.45	0.5	0.55	0.585	0.6	0.585	0.55	0.5	0.45	0.415
8	0.336	0.349	0.378	0.42	0.462	0.491	0.504	0.491	0.462	0.42	0.378	0.349
9	0.344	0.357	0.387	0.43	0.473	0.503	0.516	0.503	0.473	0.43	0.387	0.357
10	0.396	0.411	0.446	0.495	0.545	0.579	0.594	0.579	0.545	0.495	0.446	0.411
11	0.426	0.442	0.48	0.533	0.586	0.624	0.64	0.624	0.586	0.533	0.48	0.442
12	0.553	0.574	0.622	0.691	0.76	0.808	0.829	0.808	0.76	0.691	0.622	0.574
13	0.415	0.431	0.467	0.519	0.571	0.607	0.623	0.607	0.571	0.519	0.467	0.431
14	0.334	0.347	0.376	0.418	0.46	0.489	0.502	0.489	0.46	0.418	0.376	0.347
15	0.318	0.33	0.357	0.397	0.437	0.464	0.476	0.464	0.437	0.397	0.357	0.33
16	0.327	0.339	0.368	0.409	0.45	0.479	0.491	0.479	0.45	0.409	0.368	0.339
17	0.526	0.546	0.592	0.658	0.724	0.77	0.79	0.77	0.724	0.658	0.592	0.546
18	0.985	1.022	1.108	1.231	1.354	1.44	1.477	1.44	1.354	1.231	1.108	1.022
19	0.802	0.832	0.903	1.003	1.103	1.174	1.204	1.174	1.103	1.003	0.903	0.832
20	0.541	0.561	0.608	0.676	0.744	0.791	0.811	0.791	0.744	0.676	0.608	0.561
21	0.384	0.398	0.432	0.48	0.528	0.562	0.576	0.562	0.528	0.48	0.432	0.398
22	0.24	0.249	0.27	0.3	0.33	0.351	0.36	0.351	0.33	0.3	0.27	0.249
23	0.163	0.169	0.184	0.204	0.224	0.239	0.245	0.239	0.224	0.204	0.184	0.169

In Table 6.2 is shown the average load per hour on weekends:

Table 6.2. *Average load (kW) per hour on weekends.*

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0.087	0.09	0.098	0.109	0.12	0.128	0.131	0.128	0.12	0.109	0.098	0.09
1	0.076	0.079	0.085	0.095	0.105	0.111	0.114	0.111	0.105	0.095	0.085	0.079
2	0.076	0.079	0.085	0.095	0.105	0.111	0.114	0.111	0.105	0.095	0.085	0.079
3	0.076	0.079	0.085	0.095	0.105	0.111	0.114	0.111	0.105	0.095	0.085	0.079
4	0.262	0.271	0.294	0.327	0.36	0.383	0.392	0.383	0.36	0.327	0.294	0.271
5	0.4	0.415	0.45	0.5	0.55	0.585	0.6	0.585	0.55	0.5	0.45	0.415
6	0.44	0.457	0.495	0.55	0.605	0.644	0.66	0.644	0.605	0.55	0.495	0.457
7	0.4	0.415	0.45	0.5	0.55	0.585	0.6	0.585	0.55	0.5	0.45	0.415
8	0.37	0.383	0.416	0.462	0.508	0.541	0.554	0.541	0.508	0.462	0.416	0.383
9	0.378	0.393	0.426	0.473	0.52	0.553	0.568	0.553	0.52	0.473	0.426	0.393
10	0.436	0.452	0.49	0.545	0.599	0.637	0.653	0.637	0.599	0.545	0.49	0.452
11	0.469	0.487	0.528	0.586	0.645	0.686	0.704	0.686	0.645	0.586	0.528	0.487
12	0.608	0.631	0.684	0.76	0.836	0.889	0.912	0.889	0.836	0.76	0.684	0.631
13	0.457	0.474	0.514	0.571	0.628	0.668	0.685	0.668	0.628	0.571	0.514	0.474
14	0.368	0.382	0.414	0.46	0.506	0.538	0.552	0.538	0.506	0.46	0.414	0.382
15	0.349	0.362	0.393	0.437	0.48	0.511	0.524	0.511	0.48	0.437	0.393	0.362
16	0.36	0.373	0.405	0.45	0.495	0.526	0.54	0.526	0.495	0.45	0.405	0.373
17	0.526	0.546	0.592	0.658	0.724	0.77	0.79	0.77	0.724	0.658	0.592	0.546
18	0.985	1.022	1.108	1.231	1.354	1.44	1.477	1.44	1.354	1.231	1.108	1.022
19	0.802	0.832	0.903	1.003	1.103	1.174	1.204	1.174	1.103	1.003	0.903	0.832
20	0.541	0.561	0.608	0.676	0.744	0.791	0.811	0.791	0.744	0.676	0.608	0.561
21	0.384	0.398	0.432	0.48	0.528	0.562	0.576	0.562	0.528	0.48	0.432	0.398
22	0.24	0.249	0.27	0.3	0.33	0.351	0.36	0.351	0.33	0.3	0.27	0.249
23	0.163	0.169	0.184	0.204	0.224	0.239	0.245	0.239	0.224	0.204	0.184	0.169

The scaled data daily profile per month of the load will be the one shown in Figure 6.2.:

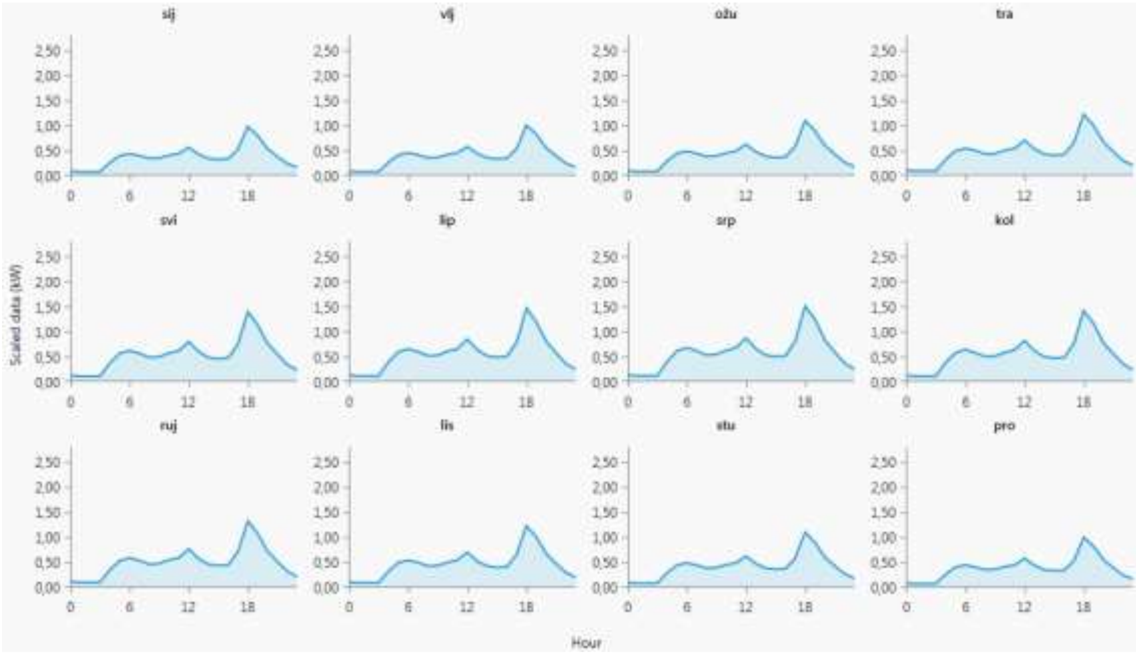

Figure 6.2. *Scaled graphs of daily load consumption per month.*

- Grid: The price of purchasing energy from the grid will be 0.140 *€/kWh*, while the price of selling the electricity to the main grid will be 0.126 *€/kWh*. Both of them at simple rates. The emissions coming from generating that electricity using the traditional power plants on which the actual grid is relying on will be: 632 *g/kWh* of Carbon Dioxide, 2.74 *g/kWh* of Sulphur Dioxide, and 1.34 *g/kWh* of Nitrogen Oxides.
- PV panels: Jinko JKM 275-60, CanadianSolar MaxPower CS6U-330p, Sharp ND-250QCS
- Batteries: Trojan SAGM 06 375, Hoppecke 24 OPzS 3000, Tesla Powerwall 2.0
- Inverter: Leonics STP-219Cp 15 kW.

6.1. PV Panels

In this project, three types of solar panels from three different manufacturing companies will be used: Jinko, Canadian Solar and Sharp. The prices of each one of the solar panels have two components, the installation price, which is calculated to be 450 € per solar panel, and the price of the panel itself. The operation and maintenance costs of the panels have been calculated assuming a 2 % of the initial cost per year We installed 5 *kW* of solar panels in each of the case studies because is enough to satisfy the consumption required by the load. The current generated by the panels is DC, they have no tracking system and the default panel slope is 45.46º.

Apart from the datasheets (that can be found in the annexes) of the equipment, we also took info from the HOMER database [9]

The Jinko JKM275-60 [10] is a flat plate solar panel, composed of 60 polycrystalline cells. We can see its most remarkable characteristics in Table 6.3.

Table 6.3. *Jinko solar panel characteristics [10]*

Capital cost/Replacement	572.40 €
O&M costs	11.45 €/year
Derating factor	88 %
Temperature coefficient	-0.41 %/*ºC*
Operating temperature	45 *ºC*
Efficiency	16.8 %
Ground reflectance	20 %
Maximum power (Pmax)	275 *W*
Maximum voltage (Vmp)	32 *V*
Maximum current (Imp)	8.61 *A*
Open-circuit voltage (Voc)	39.1 *V*
Short-circuit current (Isc)	7.44 *A*

The electrical performance and temperature dependence graphs are detailed in Figure 6.3 and 6.4

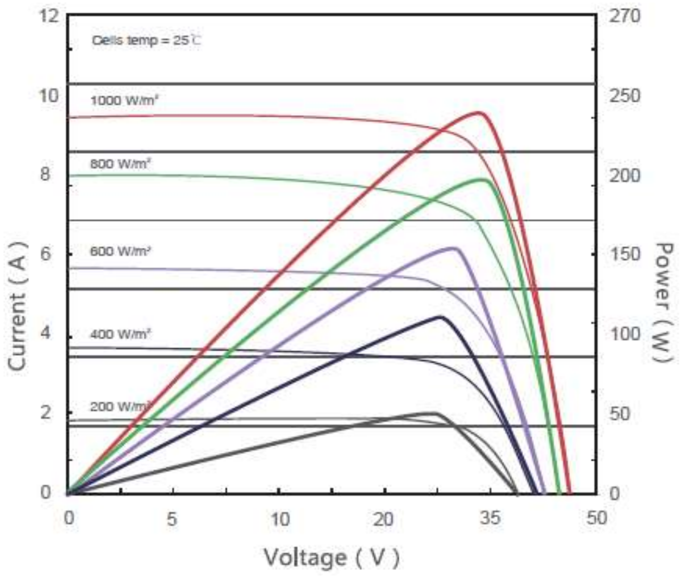

Figure 6.3. *Current-Voltage and Power-Voltage curves. [10]*

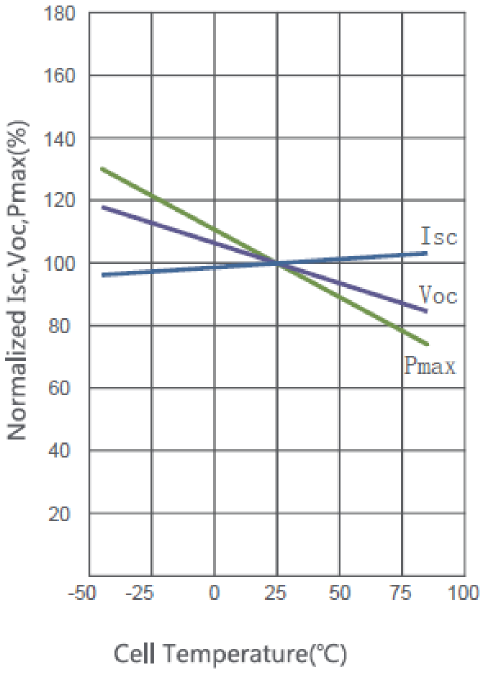

Figure 6.4. *Temperature dependence of I_{sc}, V_{oc}, P_{max}.[10]*

In Figure 6.5 we can see the engineering drawing of the Jinko solar panel.

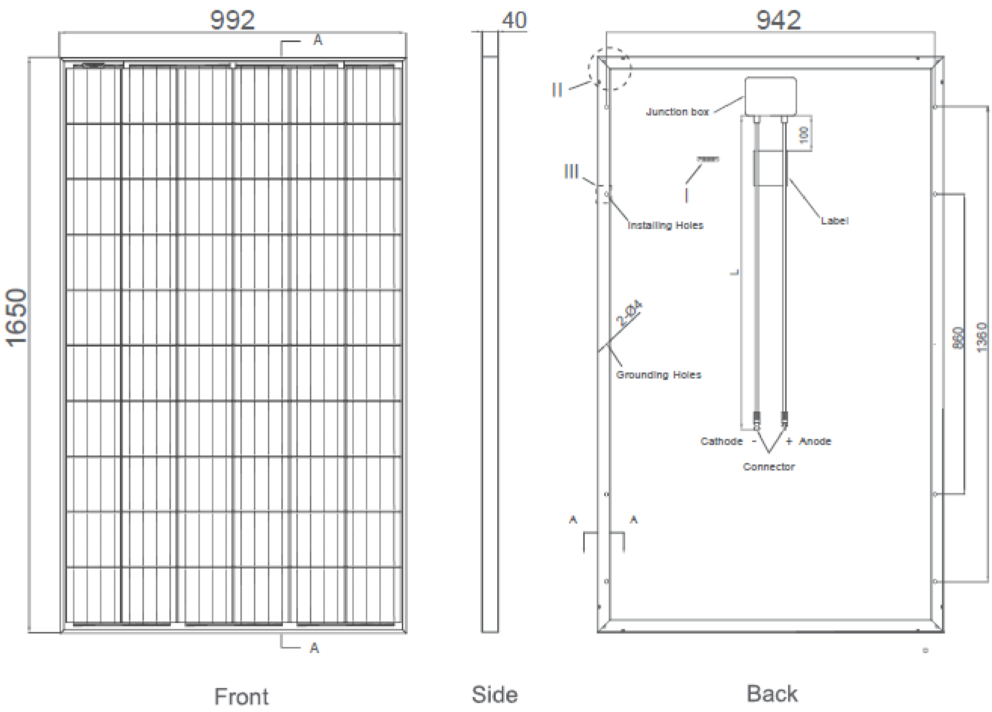

Figure 6.5. *Dimensions of the Jinko solar panel.[10]*

The CanadianSolar MaxPower CS6U-330P [11] is a flat plate solar panel, composed of 72 polycrystalline cells. We can see its most remarkable characteristics in the Table 6.4

Table 6.4. *CanadianSolar solar panel characteristics. [11]*

Capital cost/Replacement	632.12 €
O&M costs	12.64 €/year
Derating factor	88 %
Temperature coefficient	-0.41 %/*ºC*
Operating temperature	45 *ºC*
Efficiency	16.97 %
Ground reflectance	20 %
Maximum power (Pmax)	330 *W*
Maximum voltage (Vmp)	37.5 *V*
Maximum current (Imp)	8.80 *A*
Open-circuit voltage (Voc)	45.9 *V*
Short-circuit current (Isc)	9.31 *A*

The electrical performance and temperature dependence graphs are detailed in Figure 6.6.

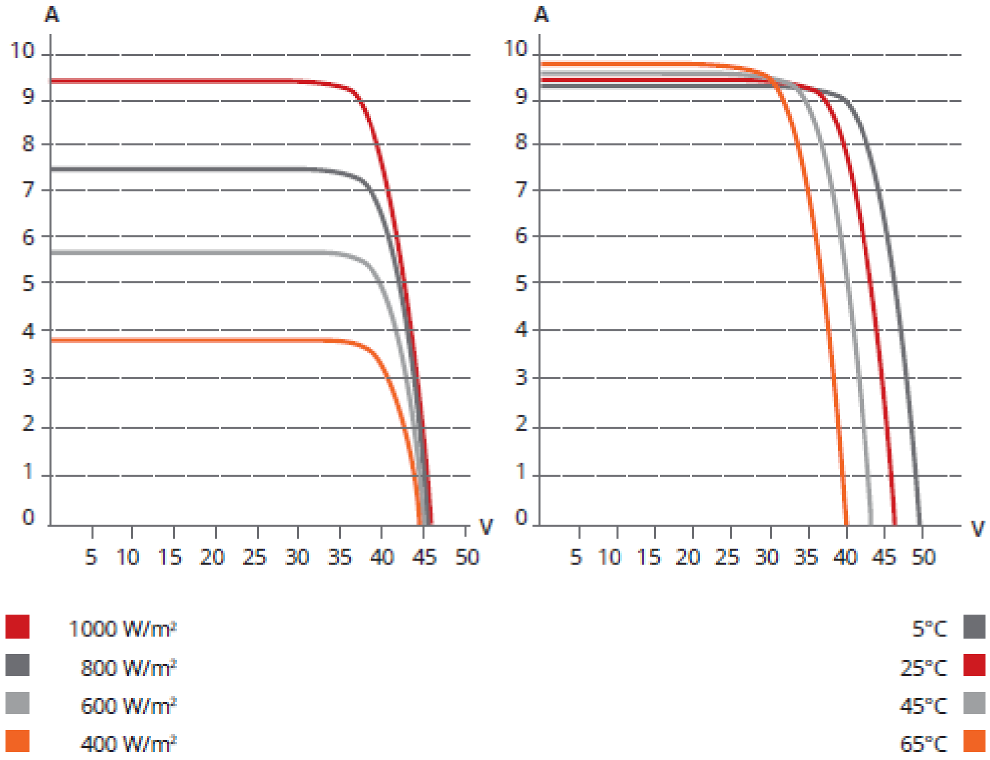

Figure 6.6. *I-V curves of the CanadianSolar solar panel.[11]*

In Figure 6.7 we can see the engineering drawing of the CanadianSolar solar panel.

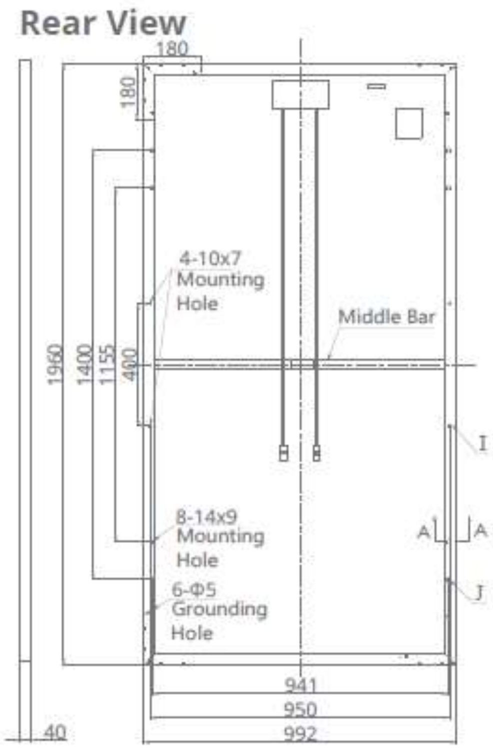

Figure 6.7. *Dimensions of the CanadianSolar solar panel. [11]*

The Sharp ND-250QCS [12] is a flat plate solar panel, composed of 60 polycrystalline silicon cells. We can see its most remarkable characteristics in the Table 6.5.

Table 6.5. *Sharp solar panel characteristics. [12]*

Capital cost/Replacement	688,10 €
O&M costs	13,76 €/year
Derating factor	88 %
Temperature coefficient	-0,485 %/ºC
Operating temperature	47,5 ºC
Efficiency	15,3 %
Ground reflectance	20 %
Maximum power (Pmax)	250 W
Maximum voltage (Vmp)	29,8 V
Maximum current (Imp)	8,40 A
Open-circuit voltage (Voc)	38,3 V
Short-circuit current (Isc)	8,90 A

In Figure 6.8 we can see the engineering drawing of the Sharp solar panel.

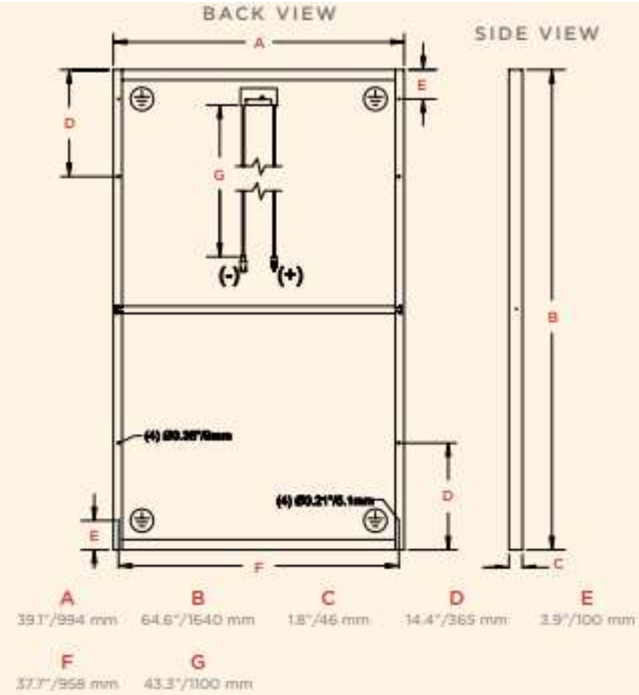

Figure 6.8. *Dimensions of the Sharp solar panel. [12]*

6.2. Batteries

In the case study where we do not count with the support of the utility, batteries are vital for the correct functioning of the microgrid. We left Homer optimize the correct amount of batteries needed in every scenario. The operation and maintenance costs of the batteries have also been calculated assuming a 2% of the initial cost per year.

The Trojan Solar SAGM 06 375 [13] is a lead-acid battery with a warranty of 8 years, we can see some of its characteristics in Table 6.6.

Table 6.6. *Trojan batteries characteristics. [13]*

Capital cost/Replacement	480 €
O&M costs	9.6 €/year
Lifetime throughput	2,136.10 *kWh*
Nominal Voltage	6 *V*
Nominal Capacity	2.46 *kWh*
Maximum Capacity	409 *Ah*
Capacity ratio	0.536
Roundtrip efficiency	85 %
Maximum charge current	75 *A*
Maximum discharge current	300 *A*
Depth of discharge (DoD)	80 %

The datasheet of the Trojan batteries include some graphs that we can see in Figures 6.9, 6.10, 6.11, and 6.12 where it's depicted the solar cycle-life, the capacity vs operating temperature, the discharge and performance through time, respectively:

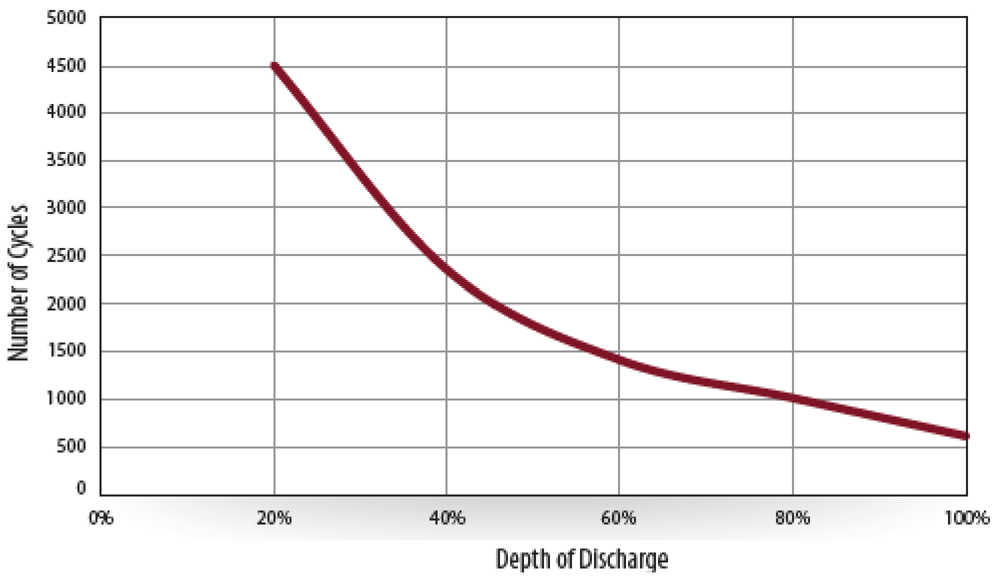

Figure 6.9. *Solar cycle-life of the Trojan battery. [13]*

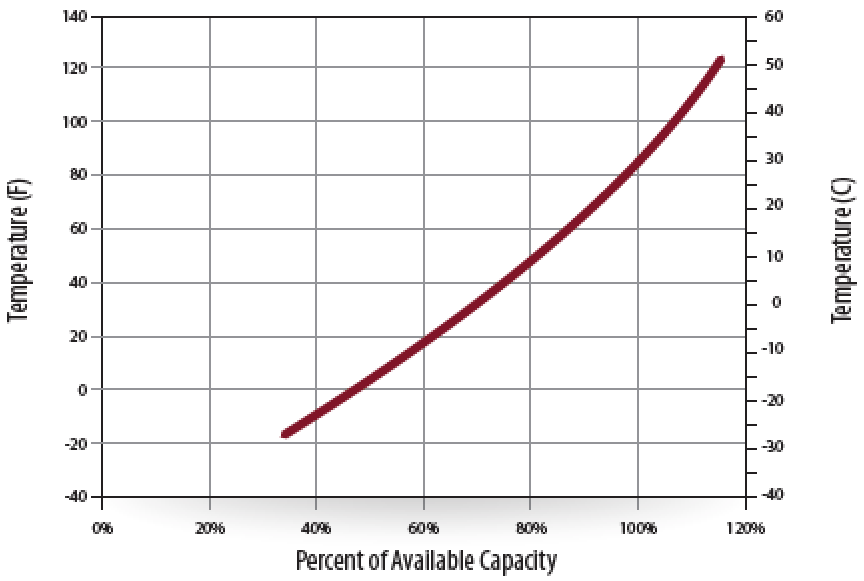

Figure 6.10. *Capacity vs operating temperature of the Trojan battery. [13]*

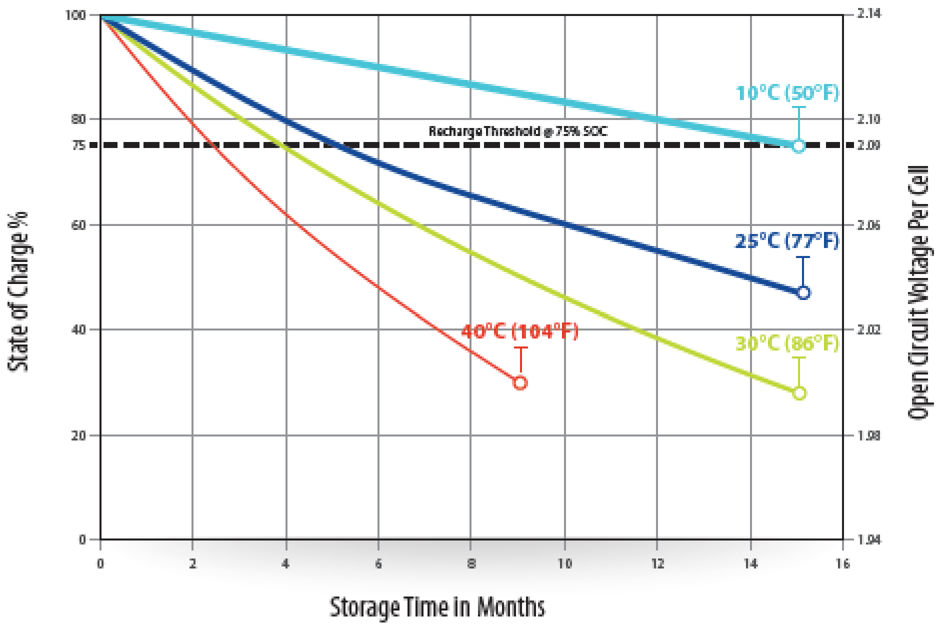

Figure 6.11. *Self-discharge vs time of the Trojan battery. [13]*

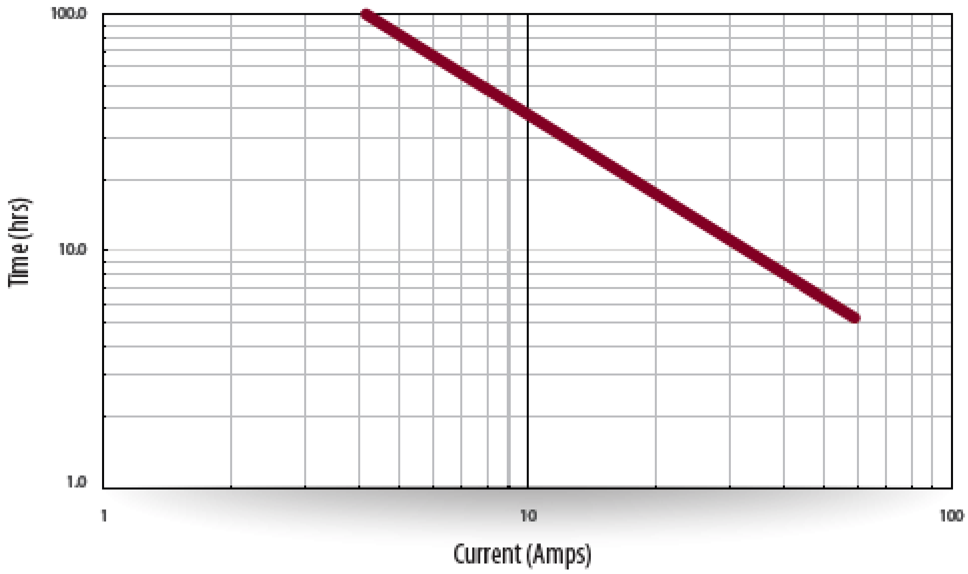

Figure 6.12. *Performance of the Trojan battery. [13]*

The Hoppecke 24 OPzS 3000 [14] is a lead-acid battery with a designed lifetime of 20 years. The basic characteristics are shown in Table 6.7.

Table 6.7. *Hoppecke batteries characteristics. [14]*

Capital cost/Replacement	1,500 €
O&M costs	30 €/year
Lifetime throughput	10,118.30 *kWh*
Nominal Voltage	2 *V*
Nominal Capacity	7.15 *kWh*
Maximum Capacity	3,570 *Ah*
Capacity ratio	0.315
Roundtrip efficiency	86 %
Maximum charge current	610 *A*
Maximum discharge current	610 *A*
Depth of discharge (DoD)	70 %

The Tesla Powerwall 2.0 [15] is a Lithium-Ion battery with a 10-year warranty, its characteristics are detailed in Table 6.8.

Table 6.8. *Tesla battery characteristics. [15]*

Capital cost/Replacement	6,500 €
O&M costs	130 €/year
Lifetime throughput	67,500 *kWh*
Nominal Voltage	220 *V*
Nominal Capacity	13.2 *kWh*
Nominal Capacity	60 *Ah*
Capacity ratio	0.315
Roundtrip efficiency	89 %
Maximum charge current	31.8 *A*
Maximum discharge current	31.8 *A*
Depth of discharge (DoD)	100 %

6.3. Inverter

Our inverter is the Leonics STP-219Cp [16], a high efficiency stand-alone three-phase bi-directional inverter with built-in output transformer. We will be using a 3 *kW* model, which costs

600 € (also for replacement), and has an operation and maintenance cost of 12 €. The inverter has an efficiency of 96 % and an expected lifetime of 10 years, while the rectifier has an efficiency of 94 % and a relative capacity of 80 %. It has an audible alarm for low battery, inverter fault, overload, short circuit and overheating. The THD of the inverter is less than 3 % in total and its waveform is a pure sine wave. We can see the appearance of the inverter in Figure 6.13.

Figure 6.13. *The Leonics inverter. [16]*

7. Simulations

7.1. On-grid microgrid with cheapest equipment

After we explained the basic concepts of the elements of our microgrid, we can start showing the results of the simulations carried out using HOMER Pro. First, we start with the microgrid connected to the utility with the cheapest equipment, namely, the Jinko solar panels. The scheme of the microgrid will look like is shown in Figure 7.1.:

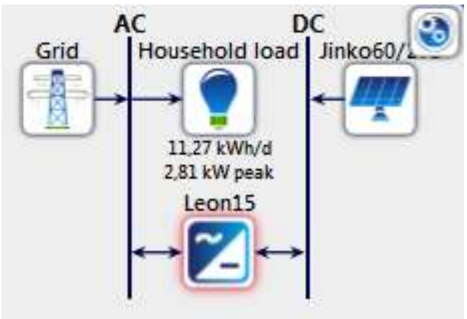

Figure 7.1. *Scheme of the microgrid.*

The batteries had to be removed from the simulations of the on-grid microgrids because the program didn’t use them, as it searches for the optimization of the price, and the batteries are the equipment that cost more money. After 8 simulations the HOMER software shows us a summary of the results, as shown in Table 7.1.

Table 7.1. *Summary of the simulation.*

LCOE	0,0522 €
NPC	5468 €
Operating cost	62,37 €
Initial capital	4662 €
Renewable fraction	67,8 %
Capital cost of the PV panels	2862 €
Production of the PV panels	6472 kWh
Inverter mean output	0,627 kW
Inverter capital cost	1800 €
Energy purchased from the grid	2612 kWh
Energy sold to the grid	3991 kWh

While this is a summary of the microgrid using the solar panels, HOMER also offers you the results of the simulation in the case where only the main grid is being used. In that case, the LCOE would have been of 0.140 €, the NPC 7,445 € and the operating cost 575.90 €. Of course, we would not have an initial capital investment.

To compare the economics of the two possible solutions to the simulation, HOMER offers the Table 7.2:

Present worth	1,977 €
Annual worth	185 €/year
Return on investment	11 %
Internal rate of return	10.3 %
Simple payback	7.52 years
Discounted payback	13.55 years

Table 7.2. *Compared economics between optimal solution and only using the grid.*

In Figure 7.2 we can see the graph of the cost summary and in Table 7.3 the breakdown of the NPC.

Table 7.3. *Breakdown of the costs.*

Component	**Capital**	**Replacement**	**O&M**	**Salvage**	**Total**
Grid	0 €	0 €	-1,773.66 €	0 €	-1,773.66 €
PV system	2,862 €	0 €	739.97 €	0 €	3,601.97 €
Inverter	1,800 €	1590.19 €	465.39 €	-215.60 €	3,639.98 €
System	4,662 €	1,590.19 €	-568.30 €	-215.60 €	5,468.29 €

As we've seen, the operation and maintenance costs of the grid are negative, that's because of the energy we sell to the utility.

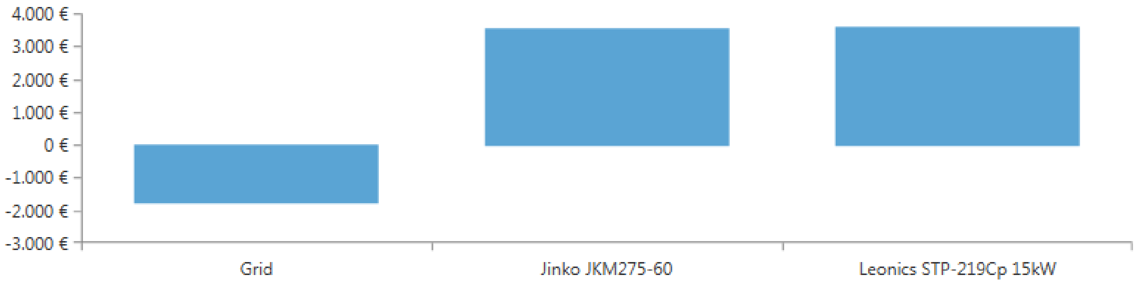

Figure 7.2. *Summary of costs.*

In Figure 7.3 we have the discounted cash flow by cost type of our microgrid in the 25 years of the duration of the project.

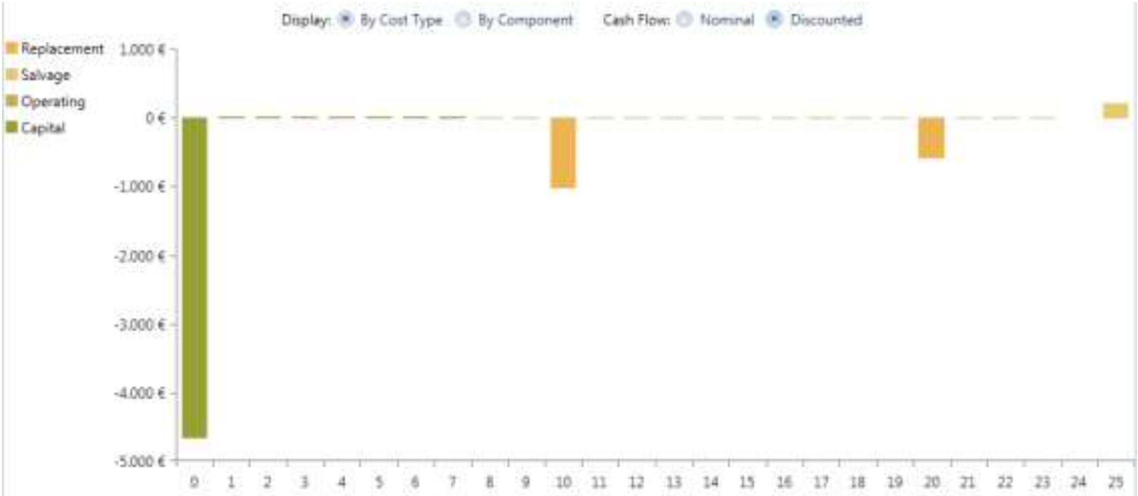

***Figure 7.3.:** Cash flow.*

As to the electrical performance of our microgrid, the total production of our system is 9,084 *kWh*/year: 6,472 *kWh*/year produced by the Jinko solar panels (71.2%) and 2,612 *kWh*/year from grid purchases (28.8%). The consumption of our load is 4,114 *kWh*/year, and adding the 3,991 *kWh*/year of grid sales, we have our total consumption that ascends to 8,105 *kWh*/year. Is remarkable than almost half of our consumption (49.2%) is destined to grid sales, making the microgrid economically viable. We have an excess electricity of 750 *kWh*/year (the 8.26% of our production) but we don't have unmet electric load or capacity shortages, so the microgrid is reliable in terms of electrical performance. In Figure 7.4 we can see the average electricity production per month which, as stated before, will match perfectly with our electricity needing from the load and also, especially during the daylight, we will be able to sell electricity to the grid.

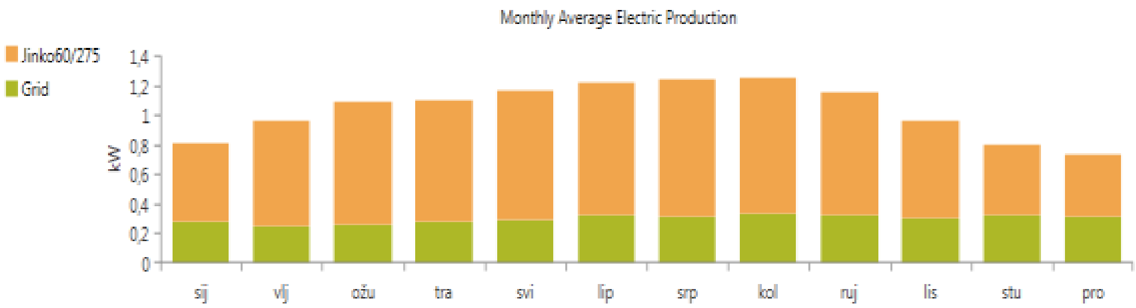

***Figure 7.4.** Monthly average electric production.*

The renewable fraction of our microgrid is 67.8%, but the maximum renewable penetration is 177%. This high value of more than the 100% is because we take into account the sales to the grid;

if we divide the total renewable production by the load, the value is 79.8%, and if we divide the same renewable production by the generation, the fraction is 71.2%.

The rated capacity of our Jinko solar panels, as we said before, is 5 *kW*. In Table 7.4 we can see some remarkable values from their functioning in our microgrid.

Table 7.4. *Jinko solar panels*

Mean output	0.739 *kW*
Mean output	17.7 *kWh*/day
Capacity factor	14.8 %
Hours of operation	4,379 hours/year
Total production	6,472 *kWh*/year
Levelized cost	0.0431 €/*kWh*

In Figure 7.5 there is the graph of the PV power output from the Jinko solar panels. We can appreciate how, logically, they produce more during the central hours of the day and during the summer.

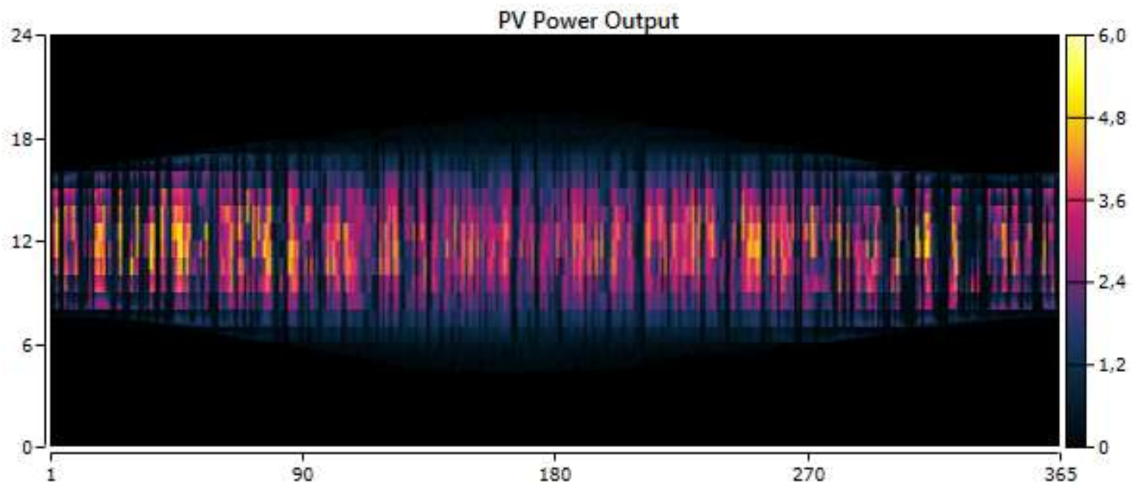

Figure 7.5. *Jinko solar panels power output per day and hour.*

The main details of the interactions with the utility are depicted in Figure 7.6, while the graph of the energy we purchase from the grid and the energy we sell to it are shown in Figures 7.7 and 7.8. As we will see, the majority of the grid sales are made also during the central hours of the day, especially on summer months, when the PV panels are functioning at the maximum. On the other hand, we make the majority of the grid purchases during the evening, when there is not enough sun for the PV panels to work so we need the back up from the utility.

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge (€)	Demand Charge (€)
January	206	252	- 46	2	-2,89 €	0 €
February	166	304	- 138	1	-15,06 €	0 €
March	194	389	- 195	2	-21,85 €	0 €
April	201	375	- 173	2	-19,02 €	0 €
May	214	405	- 191	2	-21,07 €	0 €
June	229	384	- 155	2	-16,37 €	0 €
July	234	411	- 177	2	-19,02 €	0 €
August	250	404	- 154	2	-15,91 €	0 €
September	236	359	- 122	2	-12,07 €	0 €
October	221	303	- 83	2	-7,34 €	0 €
November	232	202	30	2	7,05 €	0 €
December	228	204	25	1	6,34 €	0 €
Annual	2.612	3.991	- 1.379	2	-137,20 €	0 €

Figure 7.6. *Grid data per month.*

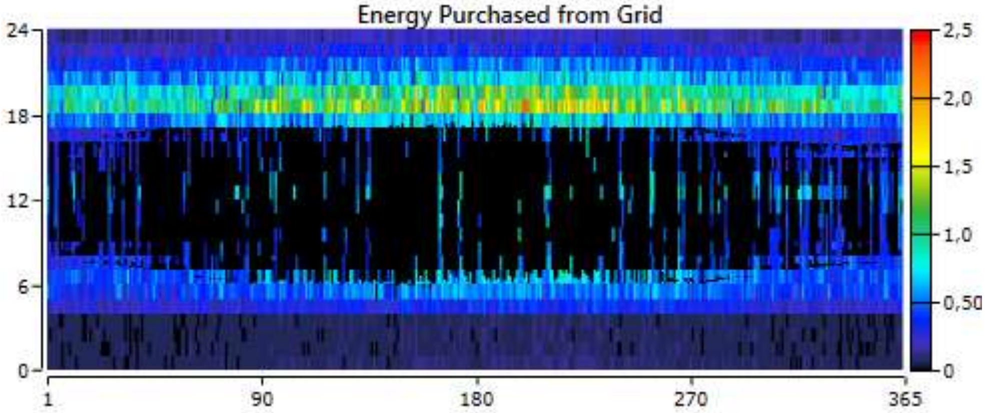

Figure 7.7. *Energy purchased from the grid per day and hour.*

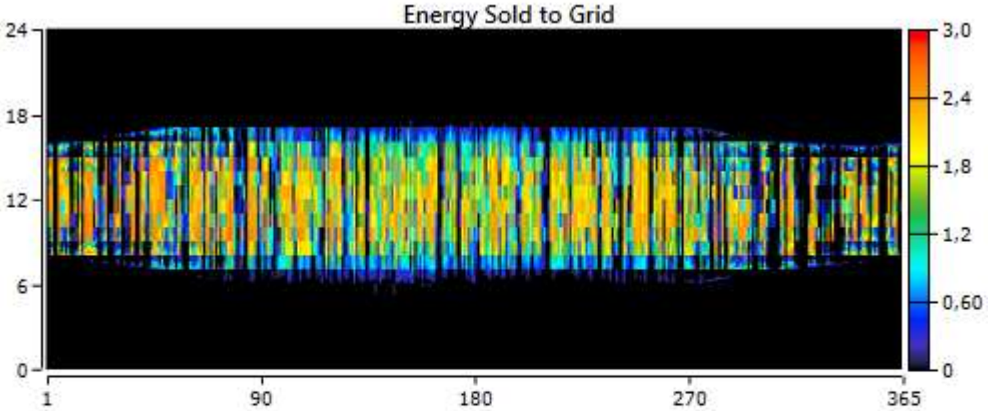

Figure 7.8. *Energy sold to the grid per day and hour.*

In Table 7.5 we can see some remarkable values from the functioning of the Leonics inverter in our microgrid.

Table 7.5. *Leonics inverter data.*

Mean output	0.627 *kW*
Maximum output	3 *kW*
Capacity factor	20.9 %
Hours of operation	2,980 hours/year
Energy out	5,493 *kWh*/year
Energy in	5,722 *kWh*/year
Losses	2,29 *kWh*/year

In Figure 7.9 is shown the graph of the inverter output, which, as expected, is functioning at the same time as the PV panels.

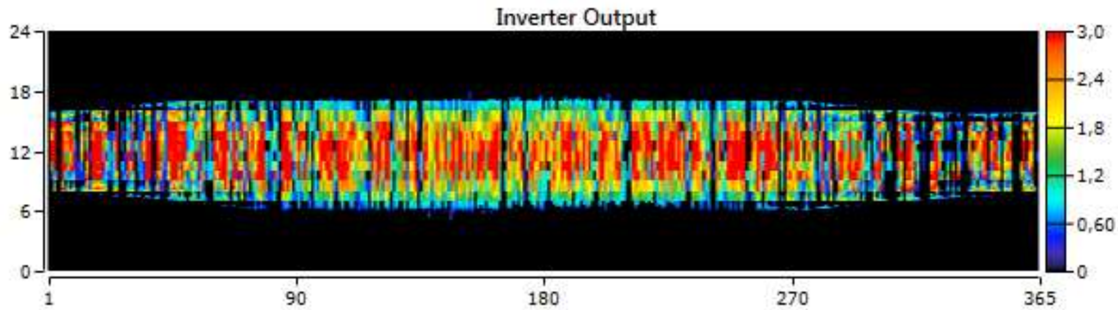

Figure 7.9. *Inverter output per day and hour.*

The gases emissions we are saving to the planet by not purchasing energy to the grid, and in addition selling to it are: 872 *kg*/year of Carbon dioxide, 3.78 *kg*/year of Sulphur dioxide and 1.85 *kg*/year of Nitrogen oxides.

7.2. On-grid microgrid with middle priced equipment

The scheme of our microgrid with the CanadianSolar panels is shown in Figure 7.10.

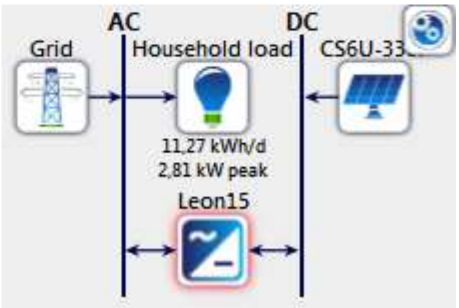

Figure 7.10.: *Scheme of the microgrid.*

After 8 simulations the HOMER software shows us a summary of the results as in Table7.6:

Table 7.6. *Summary of the simulation.*

LCOE	0.0558 €
NPC	5,843 €
Operating cost	68.29 €
Initial capital	4,961 €
Renewable fraction	67.8 %
Capital cost of the PV panels	3161 €
Production of the PV panels	6,473 *kWh*
Inverter mean output	0.627 *kW*
Inverter capital cost	1,800 €
Energy purchased from the grid	2,612 *kWh*
Energy sold to the grid	3,992 *kWh*

The comparison of the economics between the optimal solution using PV panels and the solution using only the grid (with the same costs as the simulation before), is offered by HOMER in the Table 7.7.

Table 7.7. *Compared economics between optimal solution and only using the grid.*

Present worth	1,601 €
Annual worth	150 €/year
Return on investment	10.2 %
Internal rate of return	9.2 %
Simple payback	8.08 years
Discounted payback	14.88 years

In Figure 7.11 we can see the graph of the cost summary and in Table 7.8 the breakdown of the NPC.

Table 7.8. *Breakdown of the costs.*

Component	**Capital**	**Replacement**	**O&M**	**Salvage**	**Total**
Grid	0 €	0 €	-1,774.31 €	0 €	-1,774.31 €
PV system	3,160.60 €	0 €	817.17 €	0 €	3,977.77 €
Inverter	1,800 €	1,590.19 €	465.39 €	-215.60 €	3,639.98 €
System	4,960.60 €	1,590.19 €	-491.74 €	-215.60 €	5,843.44 €

Also in this simulation, we have a negative maintenance of the grid because of the sales from the PV panels.

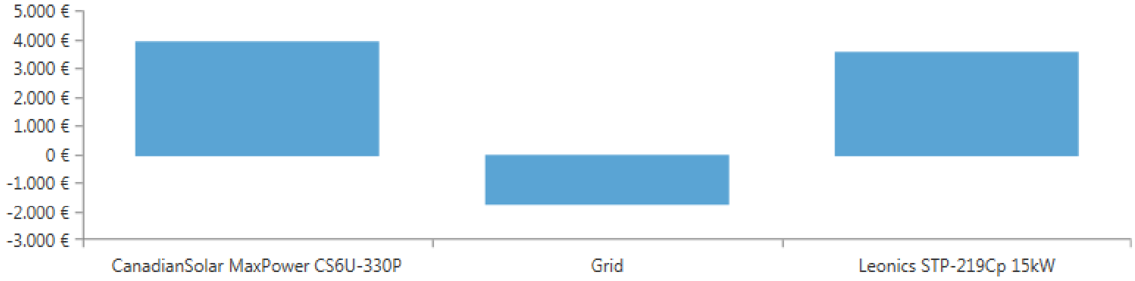

Figure 7.11. *Cost summary.*

In Figure 7.12 we can find the discounted cash flow by cost type of our microgrid in the 25 years of the duration of the project.

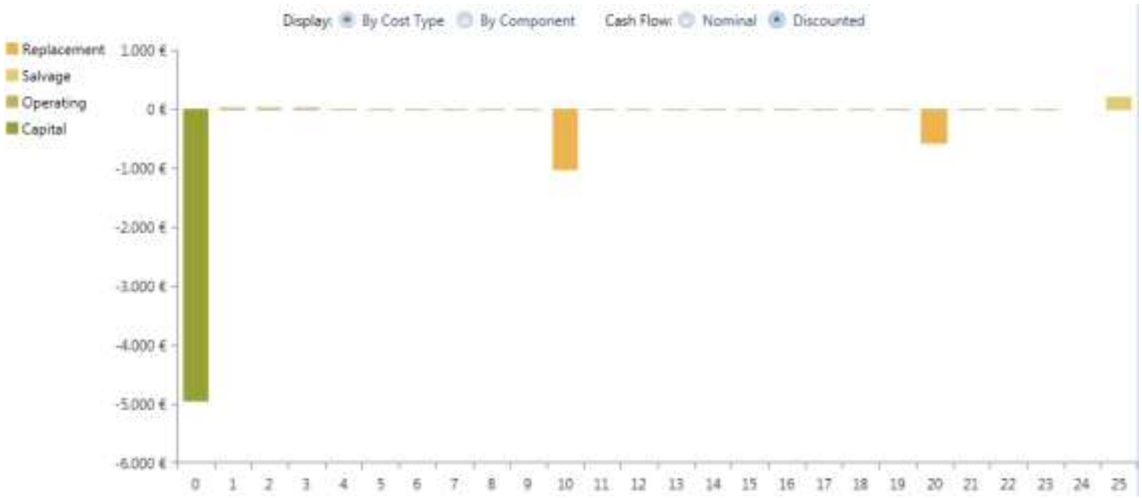

Figure 7.12. *Discounted cash flow.*

Referring to the electrical performance of this microgrid using the CanadianSolar PV panels, the total production of our system is 9,085 *kWh*/year: 6,473 *kWh*/year produced by the solar panels (71.2%) and 2,612 *kWh*/year from grid purchases (28.8%), the same amount as the previous equipment. The consumption of our load is also the same as before (and it won't change neither in the next simulation, as the load doesn't change) 4,114 *kWh*/year, and adding the 3,992 *kWh*/year of grid sales, we have our total consumption that ascends to 8,105 *kWh*/year. Is remarkable than almost half of our consumption (49.2%) is destined to grid sales, making the microgrid economically viable. We have an excess electricity of 751 *kWh*/year (the 8.26% of our production) but we don't have unmet electric load or capacity shortages again, so the microgrid is also reliable in terms of electrical performance. In Figure 7.13, we can see the average electricity production per month.

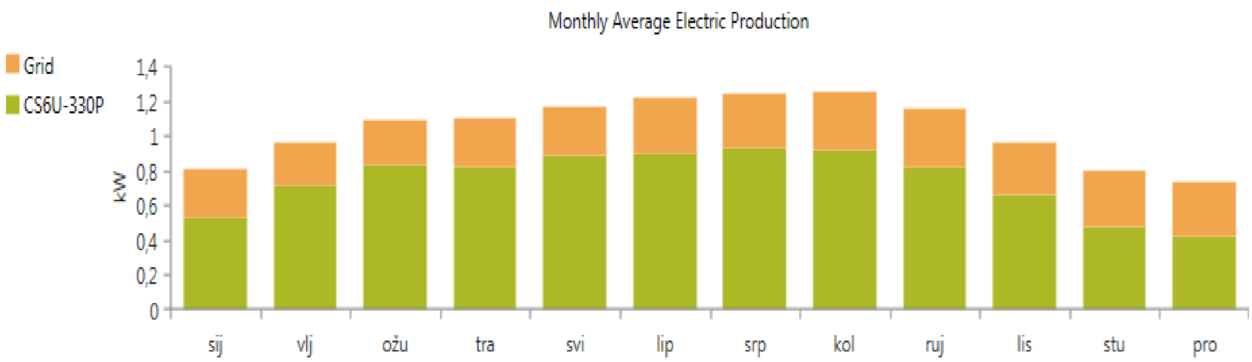

Figure 7.13. *Monthly average electric production.*

The renewable fraction of our microgrid is 67.8%, and the maximum renewable penetration is 177% again. If we divide the total renewable production by the load, the value is 79.9%, and if we divide the same renewable production by the generation, the fraction is 71.2%.

In Table 7.9 we can see some remarkable values from the functioning of the CanadianSolar panels in our microgrid.

Table 7.9. *CanadianSolar PV panels*

Mean output	0.739 *kW*
Mean output	17.7 *kWh*/day
Capacity factor	14.8 %
Hours of operation	4,379 hours/year
Total production	6,473 *kWh*/year
Levelized cost	0.0475 €/*kWh*

In Figure 7.14 we can find the graph of the PV power output from the CanadianSolar PV panels.

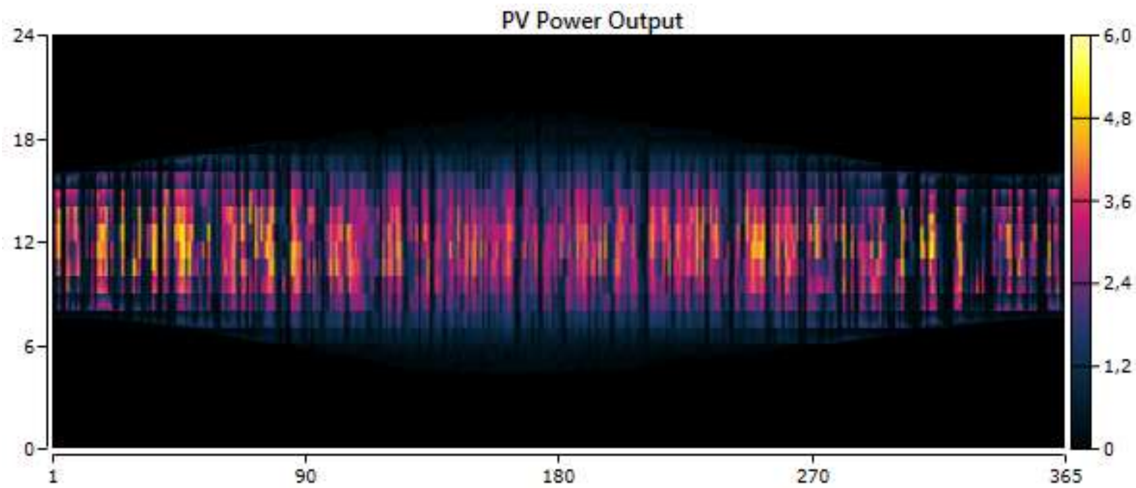

Figure 7.14. *PV power output per day and per hour.*

The main details of the interactions with the utility are depicted in Figure 7.15, while the graph of the energy we purchase from the grid and the energy we sell to it are shown in Figures 7.16 and 7.17. The interactions remain nearly exactly the same from the ones in the previous simulation; in fact, we've seen that the difference of price between the Jinko solar panels and the ones from CanadianSolar doesn't reflect in the electrical performance, and also the LCOE is higher than the one before, so we can say that is a better option to choose the cheaper equipment between these two.

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge (€)	Demand Charge (€)
January	206	252	- 46	2	-2,89 €	0 €
February	166	304	- 138	1	-15,07 €	0 €
March	194	389	- 195	2	-21,85 €	0 €
April	201	375	- 173	2	-19,02 €	0 €
May	214	405	- 191	2	-21,08 €	0 €
June	229	384	- 155	2	-16,38 €	0 €
July	234	411	- 177	2	-19,03 €	0 €
August	250	404	- 154	2	-15,92 €	0 €
September	236	359	- 122	2	-12,07 €	0 €
October	221	303	- 83	2	-7,34 €	0 €
November	232	202	30	2	7,05 €	0 €
December	228	204	25	1	6,34 €	0 €
Annual	2.612	3.992	- 1.380	2	-137,25 €	0 €

Figure 7.15. *Grid data per month.*

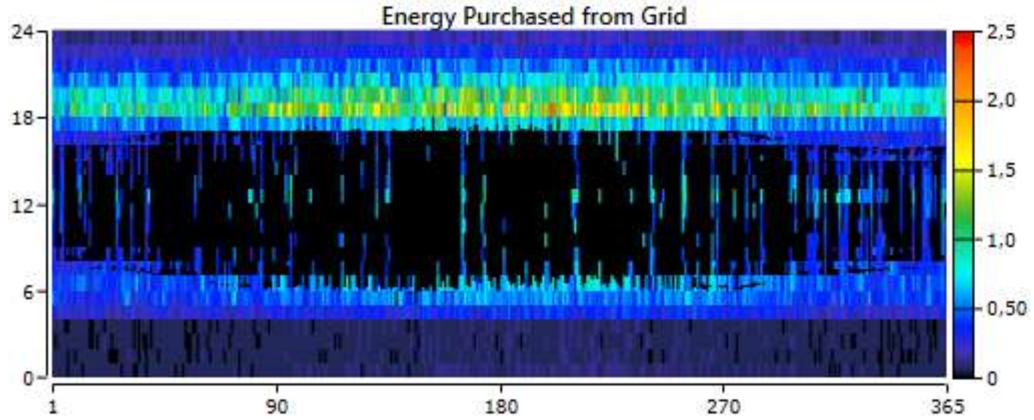

Figure 7.16. *Energy purchased from the grid per day and month.*

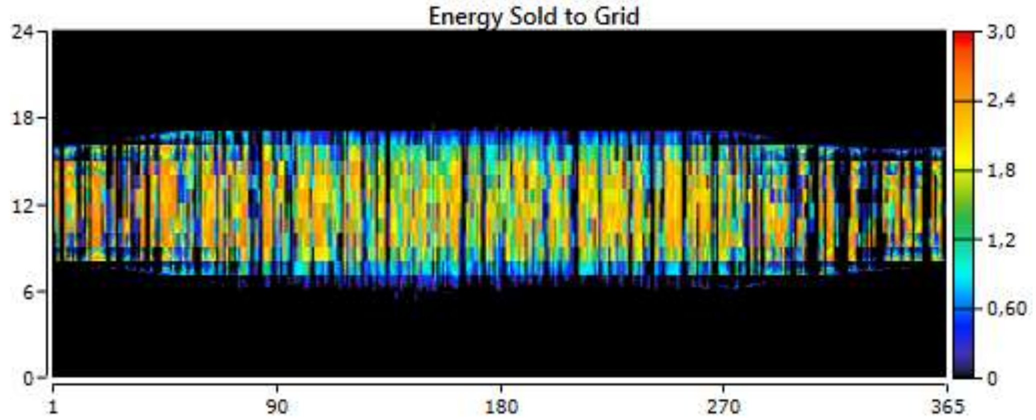

Figure 7.17. *Energy sold to the grid per day and month.*

In Table 7.10 we can see some remarkable values from the functioning of the Leonics inverter with the CanadianSolar panels.

Table 7.10. *Leonics inverter data.*

Mean output	0.627 *kW*
Maximum output	3 *kW*
Capacity factor	20.9 %
Hours of operation	2,980 hours/year
Energy out	5,493 *kWh*/year
Energy in	5,722 *kWh*/year
Losses	229 *kWh*/year

In Figure 7.18. is shown the graph of the inverter output.

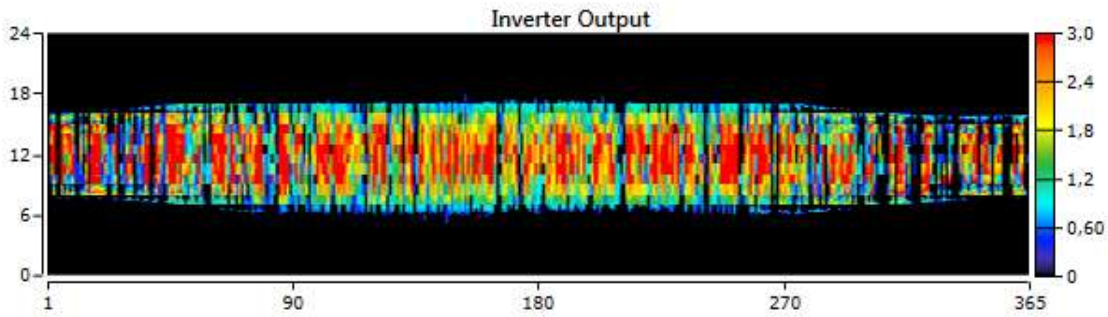

Figure 7.18. *Inverter output per day and month.*

The emissions we are saving are: 872 *kg*/year of Carbon dioxide, 3.78 *kg*/year of Sulphur dioxide and 1.85 *kg*/year of Nitrogen oxides.

7.3. On-grid microgrid with most expensive equipment

The scheme for the microgrid with the Sharp PV panels is shown in Figure 7.19.

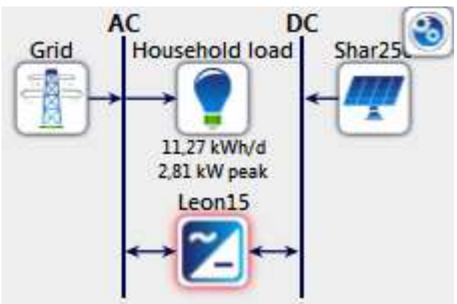

Figure 7.19. *Microgrid scheme.*

After 8 simulations the HOMER software shows us a summary of the results, depicted in Table 7.11.:

Table 7.11. *Summary of the simulation.*

LCOE	0.047 €
NPC	6,656 €
Operating cost	80.76 €
Initial capital	5,241 €
Renewable fraction	67.7 %
Capital cost of the PV panels	3440 €
Production of the PV panels	6,385 *kWh*
Inverter mean output	0.627 *kW*
Inverter capital cost	1800 €
Energy purchased from the grid	2,612 *kWh*
Energy sold to the grid	3,992 *kWh*

HOMER, as shown in the Table 7.12 offers the comparison of the economics between the optimal solution using the Sharp solar panels and the non-optimal solution:

Table 7.12. *Compared economics between optimal and non-optimal solution.*

Present worth	3,438 €
Annual worth	244 €/year
Return on investment	9.5 %
Internal rate of return	8.3 %
Simple payback	8.67 years
Discounted payback	13.33 years

In Figure 7.20 we can see the graph of the cost summary and in Table 7.13 the breakdown of the NPC.

__Table 7.13.__ Breakdown of the costs.

Component	**Capital**	**Replacement**	**O&M**	**Salvage**	**Total**
Grid	0 €	0 €	-2340,57 €	0 €	-2340,57 €
PV system	3440,50 €	0 €	1206,09 €	0 €	4646,59 €
Inverter	1800 €	2355,11 €	631 €	-436,03 €	4350,08 €
System	5240,50 €	2355,11 €	-503,48 €	-436,03 €	6656,10 €

Also in this simulation, we have a negative maintenance of the grid because of the sales from the Sharp PV panels.

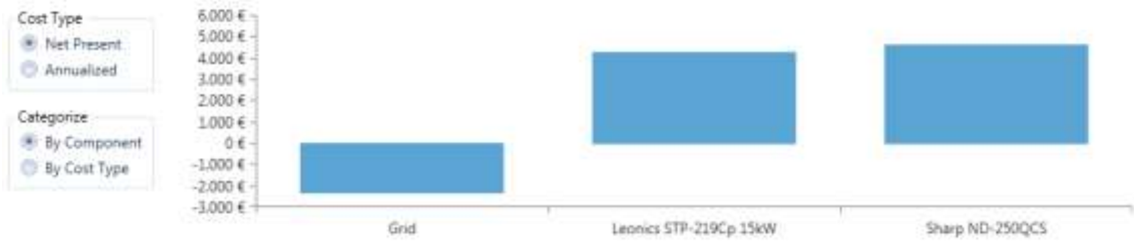

Figure 7.20. *Cost summary.*

The discounted cash flow is depicted in Figure 7.21

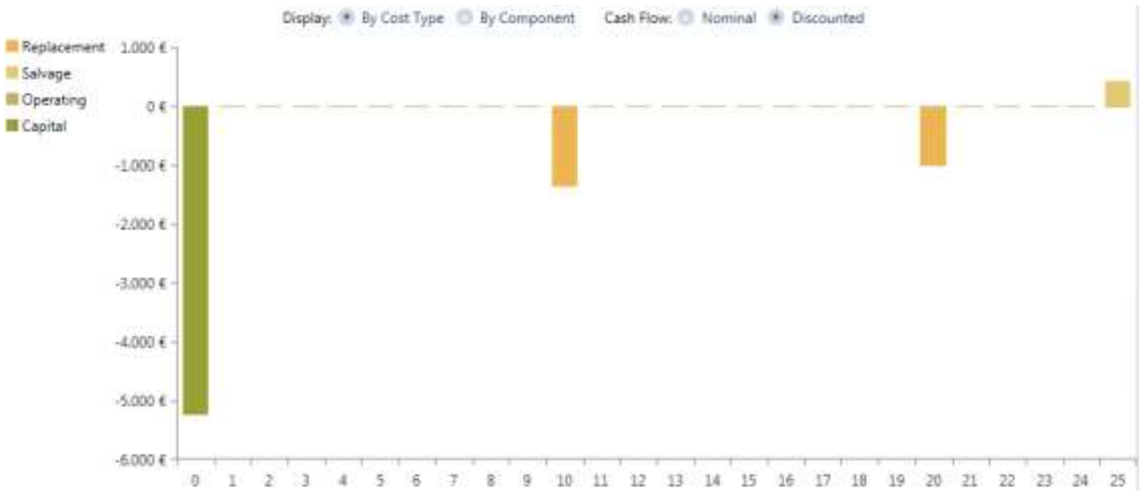

Figure 7.21. *Discounted cash flow.*

As to the electrical performance of this microgrid using the Sharp equipment, the total production of our system is 8,997 *kWh*/year: 6,385 *kWh*/year produced by the Sharp solar panels (71%) and 2,612 *kWh*/year from grid purchases (29%). The consumption of our load is also the same as before 4,114 *kWh*/year, and adding the 3,962 *kWh*/year of grid sales, we have our total consumption that ascends to 8,075 *kWh*/year. Also almost half of our consumption (49.1%) is destined to grid sales, making the microgrid economically viable. We have an excess electricity of 694 *kWh*/year (the 7.71% of our production), less than the previous equipment, meaning that these Sharp solar panels are more efficient, and we still don't have unmet electric load or capacity shortages again, so the microgrid is also reliable in terms of electrical performance. In Figure 7.22 we can see the average electricity production per month.

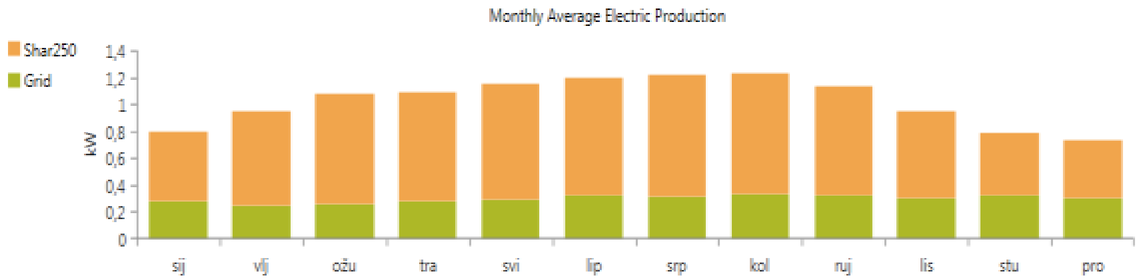

Figure 7.22. *Monthly average electric production per month.*

The renewable fraction of our microgrid is 67.7%, and the maximum renewable penetration is 172%. If we divide the total renewable production by the load, the value is 79.1%, and if we divide the same renewable production by the generation, the fraction is 71%.

In Table 7.14 we can see some remarkable values from the functioning of the CanadianSolar panels in our microgrid.

Table 7.14. *Sharp PV panels*

Mean output	0.729 *kW*
Mean output	17.5 *kWh*/day
Capacity factor	14.6 %
Hours of operation	4,379 hours/year
Total production	6,385 *kWh*/year
Levelized cost	0.0415 €/*kWh*

In Figure 7.23 we can find the graph of the PV power output from the Sharp solar panels.

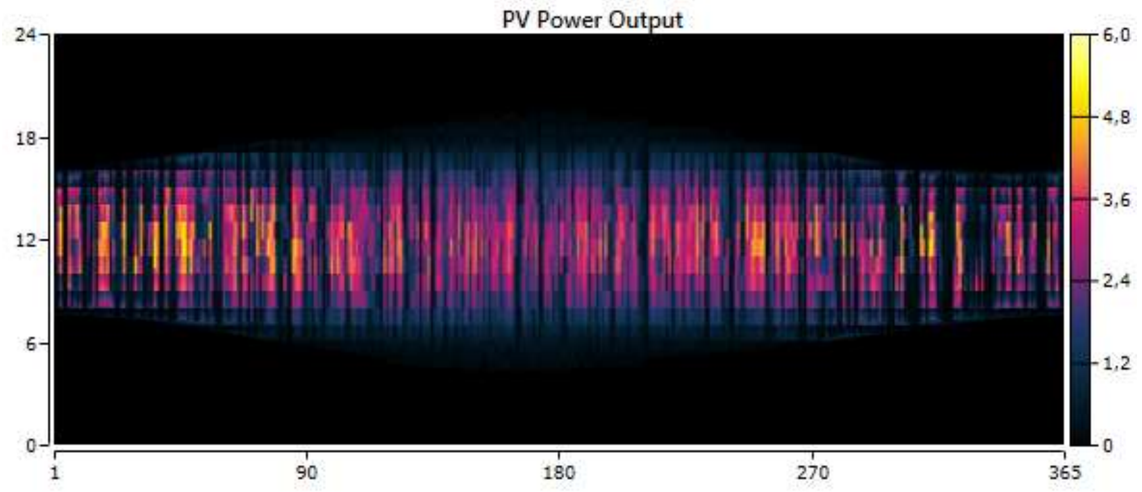

Figure 7.23. *Sharp panels power output per day and hour.*

The main details of the interactions with the utility are shown in Figure 7.24, while the graph of the energy we purchase from the grid and the energy we sell to it are shown in Figures 7.25 and 7.26.

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge (€)	Demand Charge (€)
January	206	253	- 47	2	-2,99 €	0 €
February	166	305	- 139	1	-15,18 €	0 €
March	194	389	- 195	2	-21,86 €	0 €
April	201	372	- 171	2	-18,77 €	0 €
May	214	400	- 187	2	-20,53 €	0 €
June	229	379	- 149	2	-15,63 €	0 €
July	234	404	- 169	2	-18,06 €	0 €
August	250	398	- 148	2	-15,11 €	0 €
September	236	355	- 118	2	-11,60 €	0 €
October	221	302	- 81	2	-7,12 €	0 €
November	232	202	30	2	7,04 €	0 €
December	228	204	24	1	6,27 €	0 €
Annual	2.612	3.962	- 1.350	2	-133,53 €	0 €

Figure 7.24. *Grid details.*

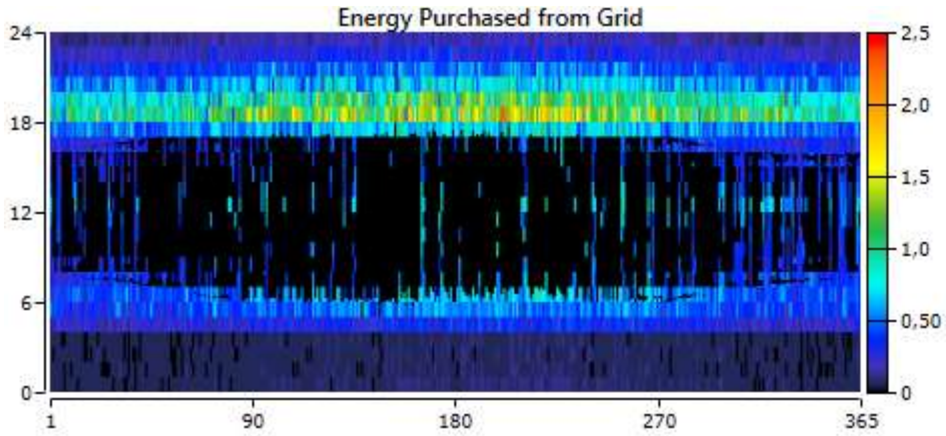

Figure 7.25. *Energy purchased from the grid per day and hour.*

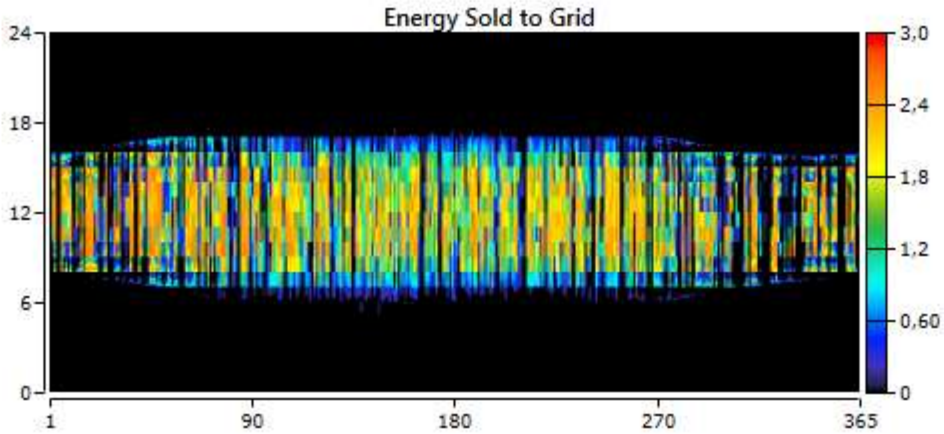

Figure 7.26. *Energy sold to the grid per day and hour.*

In Table 7.15 we can see some remarkable values from the functioning of the Leonics inverter with the Sharp panels.

Table 7.15. *Leonics inverter data.*

Mean output	0.624 *kW*
Maximum output	3 *kW*
Capacity factor	20.8 %
Hours of operation	2,981 hours/year
Energy out	5,464 *kWh*/year
Energy in	5,691 *kWh*/year
Losses	228 *kWh*/year

In Figure 7.27 is shown the graph of the inverter output.

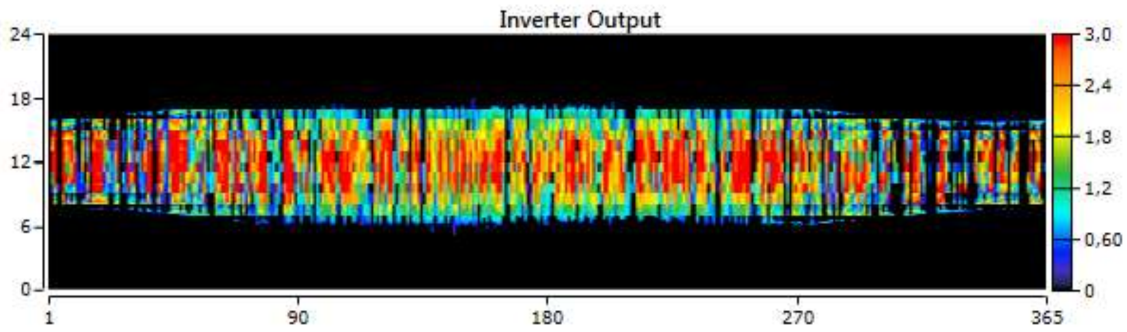

Figure 7.27. *Inverter output per day and hour*

The emissions we are saving are: 853 *kg*/year of Carbon dioxide, 3.70 *kg*/year of Sulphur dioxide and 1.81 *kg*/year of Nitrogen oxides.

7.4. Islanded microgrid with cheapest equipment

Now we start with the simulations of the off-grid microgrid. We can see the scheme of it in Figure 7.28.

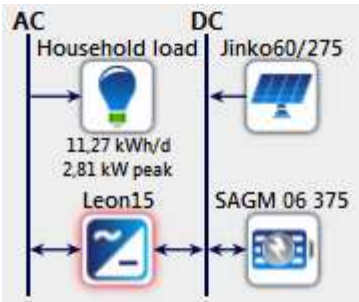

Figure 7.28. *Scheme of the off-grid microgrid.*

The summary offered by HOMER is shown in Table 7.16. Notice that now we left HOMER to optimize the number of batteries. This will increase a lot the cost of the overall microgrid, and also means that the renewable fraction is 100%, as we are relying only in the PV panels and the batteries.

Table 7.16. *Summary of the simulation.*

LCOE	0.549 €
NPC	30,782 €
Operating cost	498.16 €
Number of batteries	41
Initial capital	24,342 €
Capital cost of the PV panels	2,862 €
Production of the PV panels	6,472 *kWh*
Inverter mean output	0.469 *kW*
Inverter capital cost	1,800 €
Autonomy of the batteries	172 hours
Annual throughput of the batteries	2,591 *kWh*

In the cost summary, depicted in Figure 7.29, we can clearly see how the batteries are the equipment that rises the cost compared to the on-grid microgrids; this is because of the necessity to have a back-up source of power when the PV panels are not working and the load still needs to receive electricity. In that case, we need a large amount of batteries to face the supply of the house on their own.

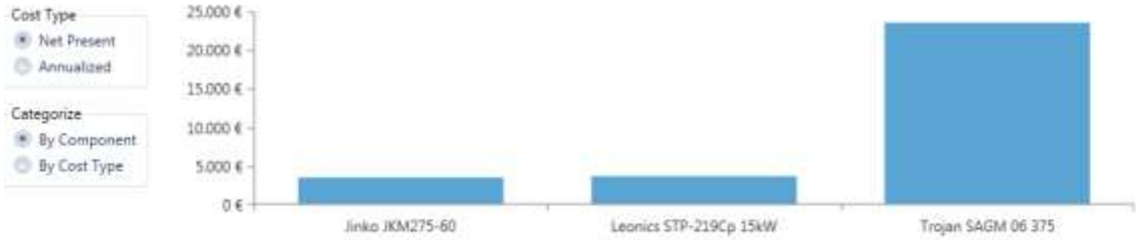

Figure 7.29. *Cost summary.*

In the following Table 7.17 we can find the detailed cost summary.

Table 7.17. *Detailed cost summary of the equipment.*

Component	Capital	Replacement	O&M	Salvage	Total
PV system	2,862 €	0 €	739.97 €	0 €	3,601.97 €
Inverter	1,800 €	1,590.19 €	465.39 €	-215.60 €	3,639.98 €
Batteries	19,680 €	0 €	5088.27 €	-1,228.20 €	23,540.07 €
System	24,342 €	1,590.19 €	6,293.63 €	-1,443.80 €	30,782.02 €

As we saw in the previous table, the batteries take the 76.47% of the total cost of the microgrid.

The discounted cash flow is presented in Figure 7.30.

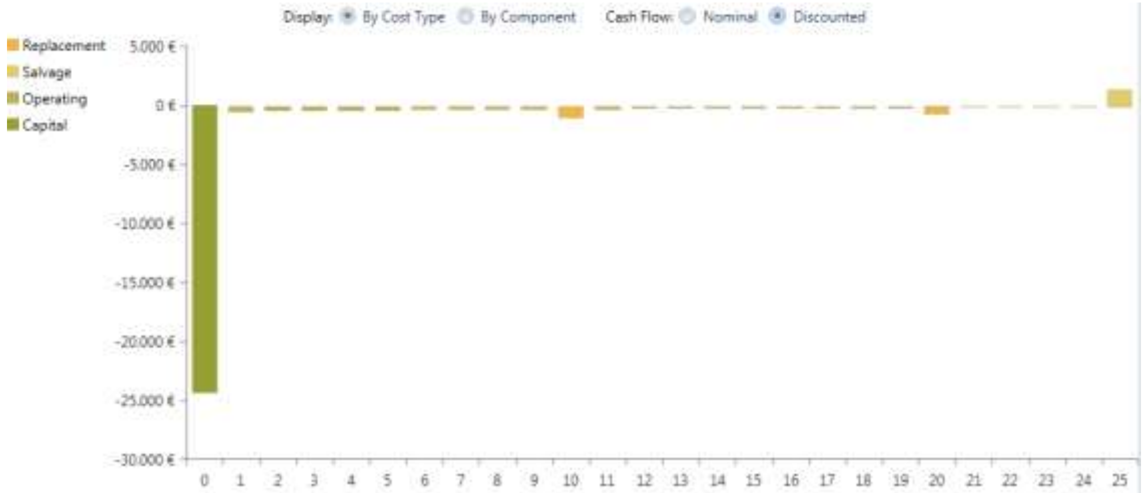

Figure 7.30. *Discounted cash flow.*

The electrical performance of this microgrid is based purely in the PV panels with the support of the batteries. In Figure 7.31 we can appreciate how almost all of the electric load is met by the PV panels generation. However, unlike the on-grid microgrid, where we counted with the backup of the utility that works 24/7, in this case study we don't have that lifesaver. In this case, we have an unmet electric load of 2.50 *kWh*/year, which represents the 0.0607 % of the total, we also have a capacity shortage of 2.86 *kWh*/year, the 0.0695 % of the total.

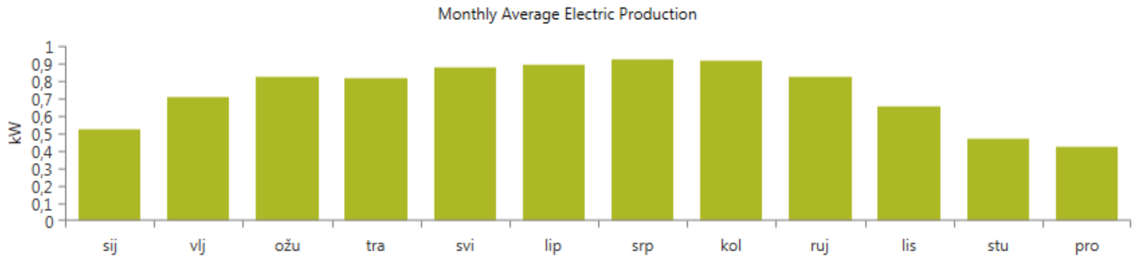

Figure 7.31. *Monthly average electricity production of the Jinko panels.*

The details on the energy production of the Jinko PV panels is shown in the following Table 7.18

Table 7.18. *Jinko PV panels*

Mean output	0.739 *kW*
Mean output	17.7 *kWh*/day
Capacity factor	14.8 %
Hours of operation	4,379 hours/year
Total production	6,472 *kWh*/year
Levelized cost	0.0431 €/*kWh*

And in the following Figure 7.32 we can see the Jinko power output

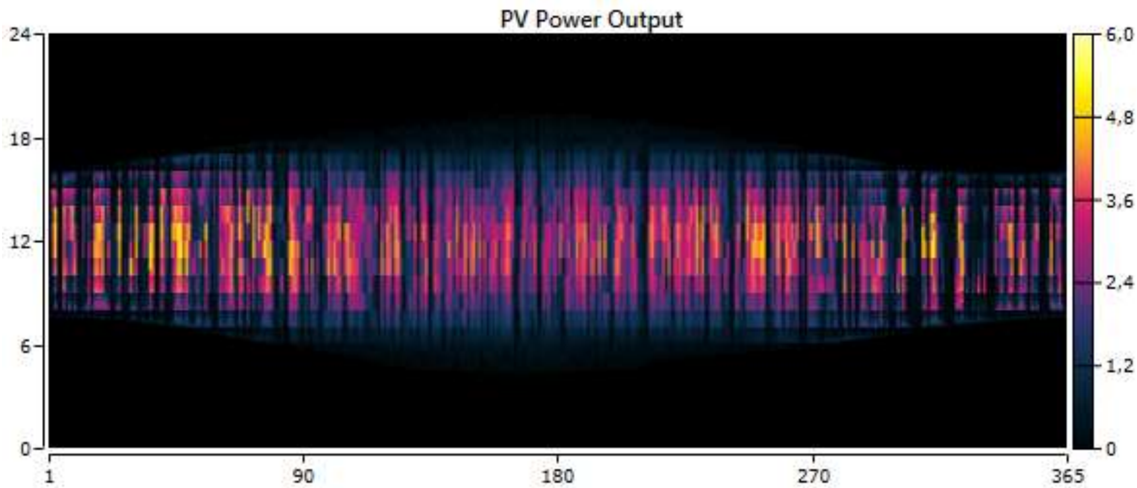

Figure 7.32. *PV power output per day and hour.*

In the Table 7.19 we can find the general information about the functioning of the 41 Trojan SAGM batteries of this microgrid.

Table 7.19. *Functioning data of the batteries.*

String size	1 battery
Strings in parallel	41 strings
Bus voltage	6 V
Energy in	2735 kWh/year
Energy out	2388 kWh/year
Storage depletion	69,4 kWh/year
Losses	416 kWh/year
Annual throughput	2591 kWh/year
Autonomy	172 hours
Storage wear cost	0,244 €/kWh
Nominal capacity	101 kWh
Usable nominal capacity	80,5 kWh
Lifetime throughput	87580 kWh
Expected life	33,8 years

We can see the state of charge of the batteries in Figure 7.33.

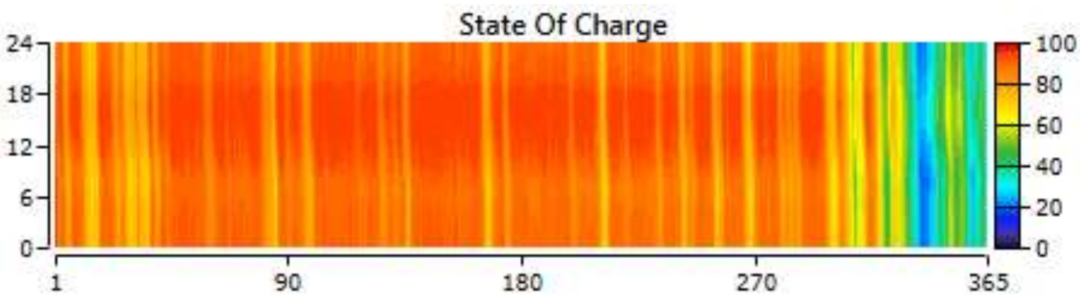

Figure 7.33. *State of charge of the batteries per day and hour.*

As is noticeable in the graph, the batteries are almost fully charged in the central hours of the day, except for those more yellow lines that correspond to cloudy days, and the winter months, where the batteries are almost discharged, and when is more suitable to have the unmet electricity load that we commented before.

The inverter in this microgrid also does the function of a rectifier and load-flow controller, as it has to distribute the energy sometimes from the solar panels to the batteries, other times from the batteries to the load and others from the solar panels directly to the load. In the following Table 7.20 we can see the important features of the Leonics inverter functioning in this microgrid.

***Table 7.20.:** Functioning of the inverter.*

Rectifier capacity	2.40 *kW*
Inverter capacity	3 *kW*
Mean output	0.469 *kW*
Maximum output	2.39 *kW*
Capacity factor	15.6 %
Hours of operation	8750 hours
Energy out	4,111 *kWh*/year
Energy in	4,282 *kWh*/year
Losses	171 *kWh*/year

In Figure 7.34 we can see how the inverter works more in the evening hours, when it has to deliver the power from the batteries to the load because the solar panels don't have eneough sun to work.

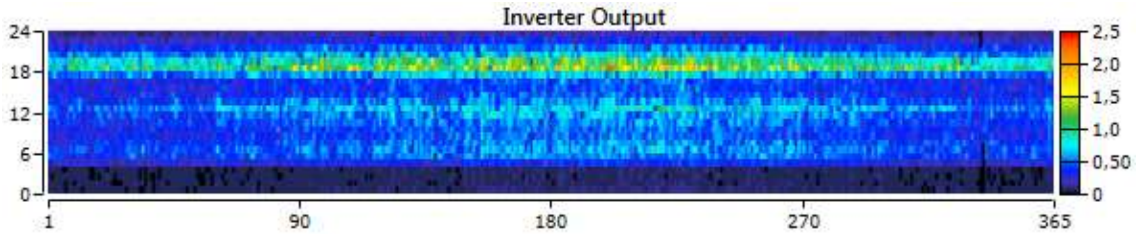

***Figure 7.34.** Inverter output per day and hour.*

In these off-grid microgrids, as we use only renewable energy sources, the emissions are zero.

7.5. Islanded microgrid with middle priced equipment

Now we are going to use the CanadianSolar PV panels and the Hoppecke batteries. Here in Figure 7.35 is the scheme of the microgrid.

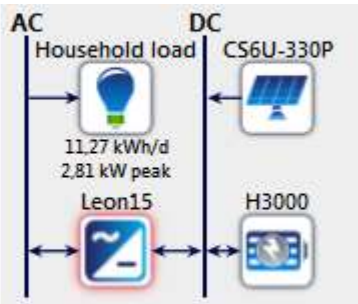

***Figure 7.35.** Scheme of the microgrid.*

The summary of the results of the optimization with HOMER are shown below in Table 7.21 As the Hoppecke batteries are better than the Trojan ones, we will need less of them, but they are also more expensive.

Table 7.21. *Summary of the simulation.*

LCOE	0,774 €
NPC	41162 €
Operating cost	943,85 €
Number of batteries	16
Initial capital	28961 €
Capital cost of the PV panels	3161 €
Production of the PV panels	6473 kWh
Inverter mean output	0,469 kW
Inverter capital cost	1800 €
Autonomy of the batteries	171 hours
Annual throughput of the batteries	2577 kWh

The cost summary is shown in Figure 7.36 and it’s also detailed in Table 7.22.

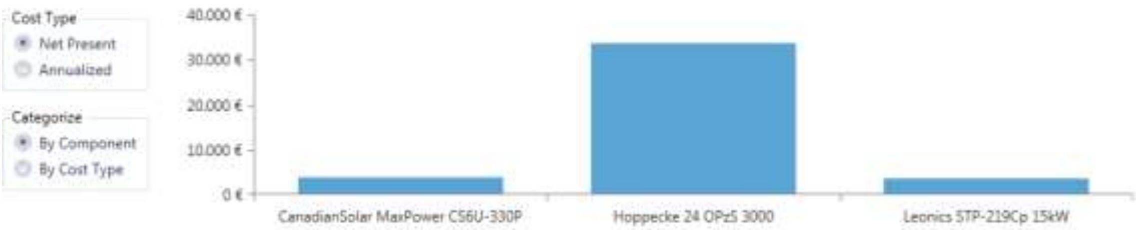

Figure 7.36. *Cost summary.*

Table 7.22. *Detailed cost summary of the equipment.*

Component	**Capital**	**Replacement**	**O&M**	**Salvage**	**Total**
PV system	3,160.60 €	0 €	817.17 €	0 €	3,977.77 €
Inverter	1,800 €	1,590.19 €	465.39 €	-215.60 €	3,639.98 €
Batteries	24,000 €	7,651.38 €	6,205.21 €	-4,312.04 €	33,544.54 €
System	28,960.60 €	9,241.56 €	7,487.77 €	-4,527.64 €	41,162.29 €

As we see clearly in the cash flow in Figure 7.37 the main difference between this microgrid and the previous one is that the Hoppecke batteries need its replacement before.

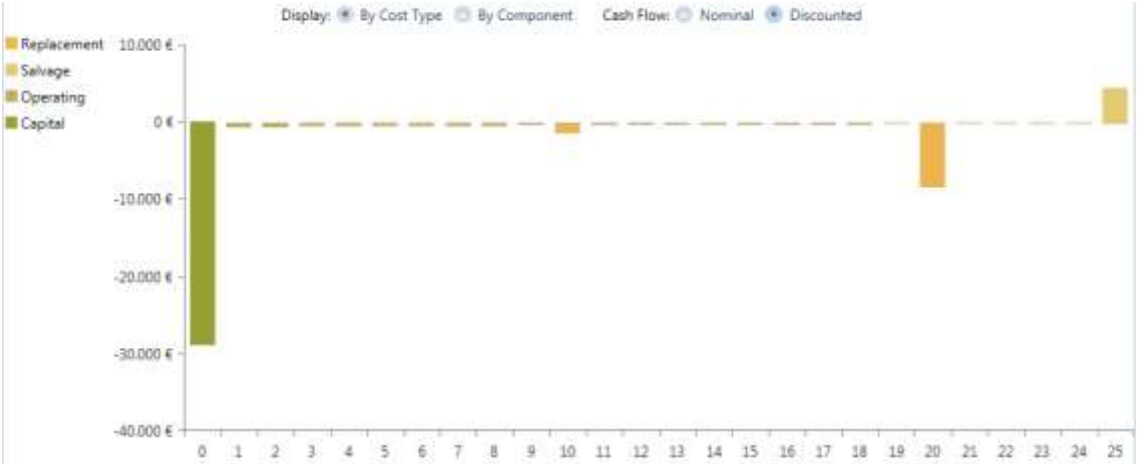

Figure 7.37 *Cash flow.*

About the electric performance, in Figure 7.38 we see the PV panels generation. In this case, we have an unmet electric load of 0.855 *kWh*/year, which represents the 0.0208 % of the total, less than the previous microgrid with the cheapest equipment. We also have less capacity shortage, 1.05 *kWh*/year, the 0.0255 % of the total. So we can say that with this equipment the electrical performance of the microgrid has improved. In Table 7.23 we can see the basic information about the solar panels in this microgrid.

Table 7.23. *CanadianSolar PV panels.*

Mean output	0.739 *kW*
Mean output	17.7 *kWh*/day
Capacity factor	14.8 %
Hours of operation	4,379 hours/year
Total production	6,473 *kWh*/year
Levelized cost	0.0475 €/*kWh*

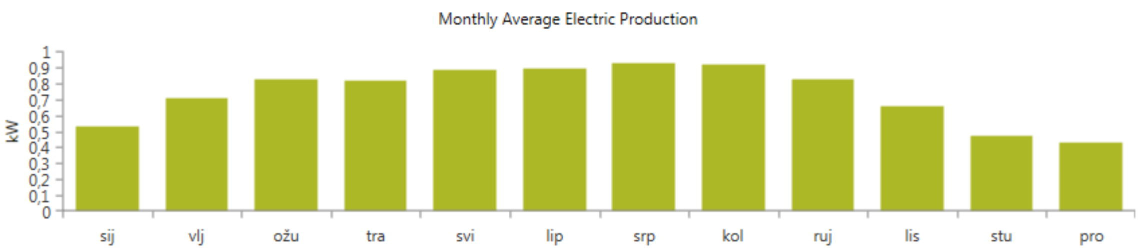

Figure 7.38. *Monthly average electric production of the PV panels.*

In the next graph, in Figure 7.39 we can see the power output from the CanadianSolar PV panels.

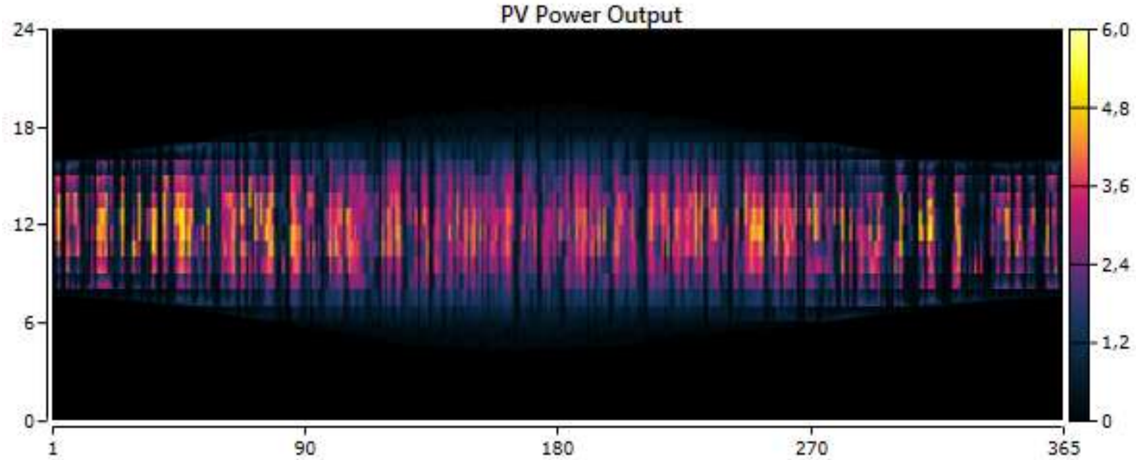

Figure 7.39. *Power output of the solar panels per day and hour.*

The functioning data of the Hoppecke batteries is shown in Table 7.24.

Table 7.24. *Functioning data of the batteries.*

String size	1 battery
Strings in parallel	16 strings
Bus voltage	2 *V*
Energy in	2,707 *kWh*/year
Energy out	2,390 *kWh*/year
Storage depletion	66.6 *kWh*/year
Losses	384 *kWh*/year
Annual throughput	2,577 *kWh*/year
Autonomy	171 hours
Storage wear cost	0.160 €/*kWh*
Nominal capacity	114 *kWh*
Usable nominal capacity	80.1 *kWh*
Lifetime throughput	51,546 *kWh*
Expected life	20 years

The state of charge of the batteries is presented in Figure 7.40.

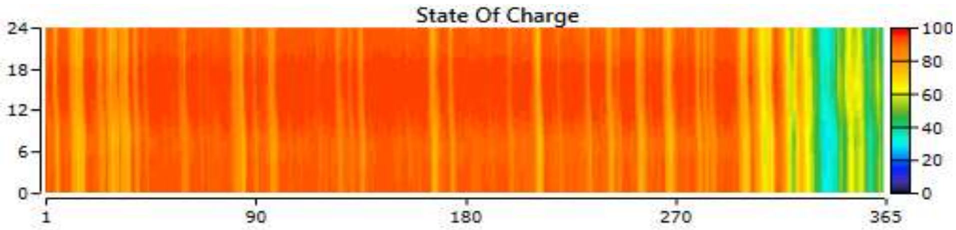

Figure 7.40. State of charge per day and hour.

The inverter functioning in the microgrid is detailed in the Table 7.25 and we can see also the inverter output in Figure 7.41.

Table 7.25. *Functioning of the inverter.*

Rectifier capacity	2.40 *kW*
Inverter capacity	3 *kW*
Mean output	0.469 *kW*
Maximum output	2.39 *kW*
Capacity factor	15.6 %
Hours of operation	8,759 hours
Energy out	4,113 *kWh*/year
Energy in	4,284 *kWh*/year
Losses	171 *kWh*/year

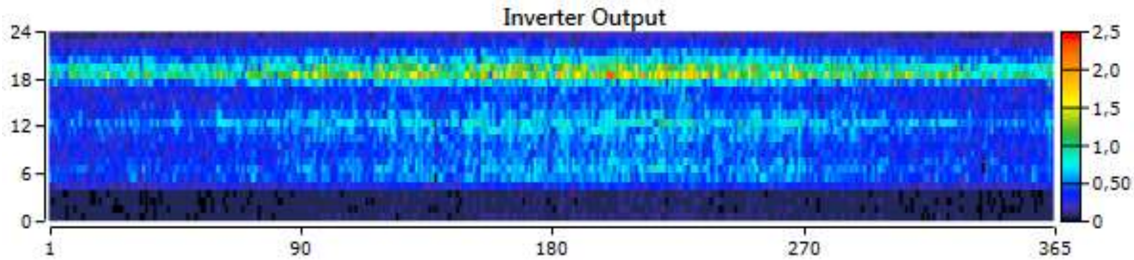

Figure 7.41. *Inverter output per day and hour.*

7.6. Islanded microgrid with most expensive equipment

In this last simulation, we will use the Sharp solar panels and the Tesla batteries as we see in the scheme of the Figure 7.42.

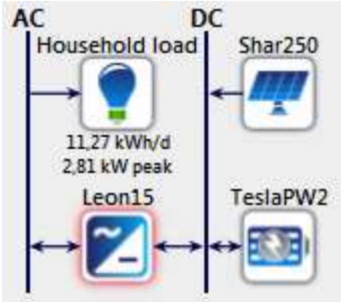

Figure 7.42. *Scheme of the microgrid.*

The summary of the results of the optimization with HOMER are shown below in Table 7.26. As the Hoppecke batteries are better than the Trojan ones, we will need less of them, but they are also more expensive.

Table 7.26. *Summary of the simulation.*

LCOE	1.63 €
NPC	86,836 €
Operating cost	3,295 €
Number of batteries	6
Initial capital	44,241 €
Capital cost of the PV panels	3,440 €
Production of the PV panels	6,385 *kWh*
Inverter mean output	0.470 *kW*
Inverter capital cost	1,800 €
Autonomy of the batteries	169 hours
Annual throughput of the batteries	2,533 *kWh*

The cost summary graph is shown in Figure 7.43 and detailed in Table 7.27.

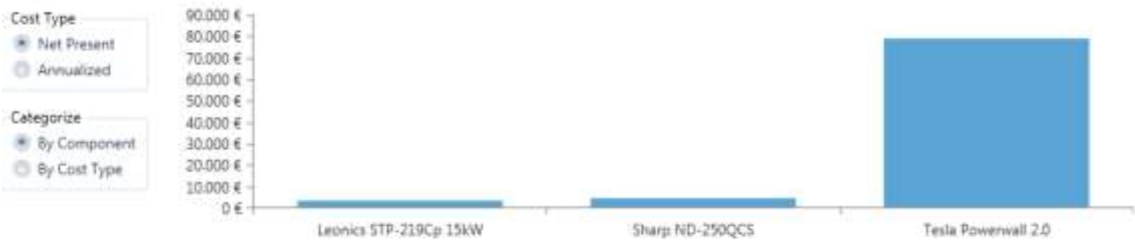

Figure 7.43. *Cost summary.*

Table 7.27.:*Detailed cost summary of the equipment.*

Component	**Capital**	**Replacement**	**O&M**	**Salvage**	**Total**
PV system	3,440.50 €	0 €	889.54 €	0 €	4,330.04 €
Inverter	1,800 €	1,590.19 €	465.39 €	-215.60 €	3,639.98 €
Batteries	39,000 €	34,454.07 €	10,083.46 €	-4,671.38 €	78,866.15 €
System	44,240.50 €	36,044.26 €	11,438.40 €	-4,886.98 €	86,836.17 €

The cash flow is shown in Figure 7.44.

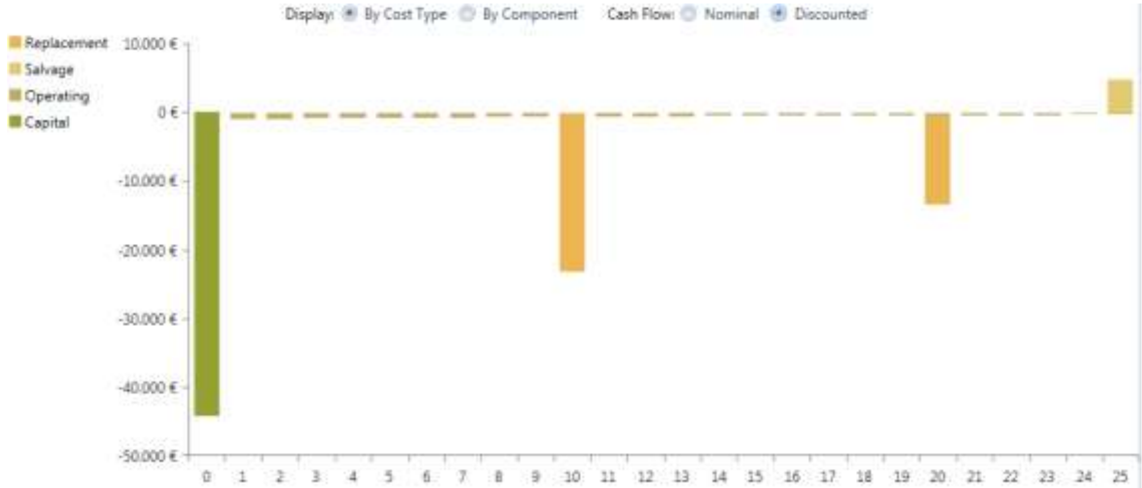

Figure 7.44. *Cash flow.*

The electric performance of the microgrid with this Tesla batteries and Sharp solar panels is better than the two off-grid microgrids that we analysed before. We don’t have an unmet electric load of or a capacity shortage, which means that we don’t leave the house without electricity at any time. In Figure 7.45 we can see the monthly average electric production of the Sharp PV panels.

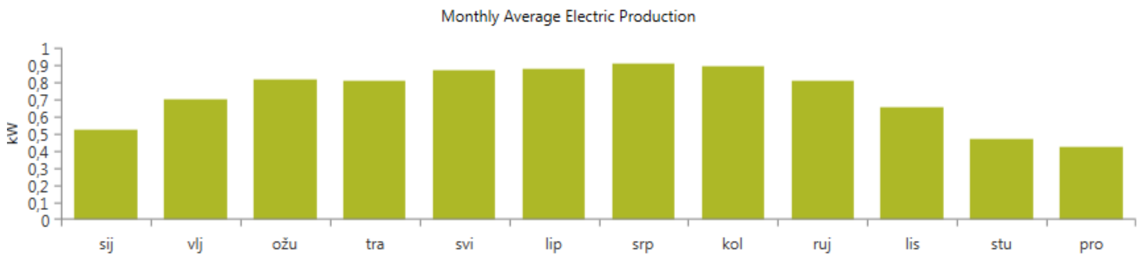

Figure 7.45. *Monthly average electric production.*

In Table 7.28 we can see the performance data of the solar panels, and in Figure 7.46 is shown the PV power output of this microgrid.

Table 7.28. *Sharp PV panels*

Mean output	0.729 *kW*
Mean output	17.5 *kWh*/day
Capacity factor	14.6 %
Hours of operation	4,379 hours/year
Total production	6,385 *kWh*/year
Levelized cost	0.0525 €/*kWh*

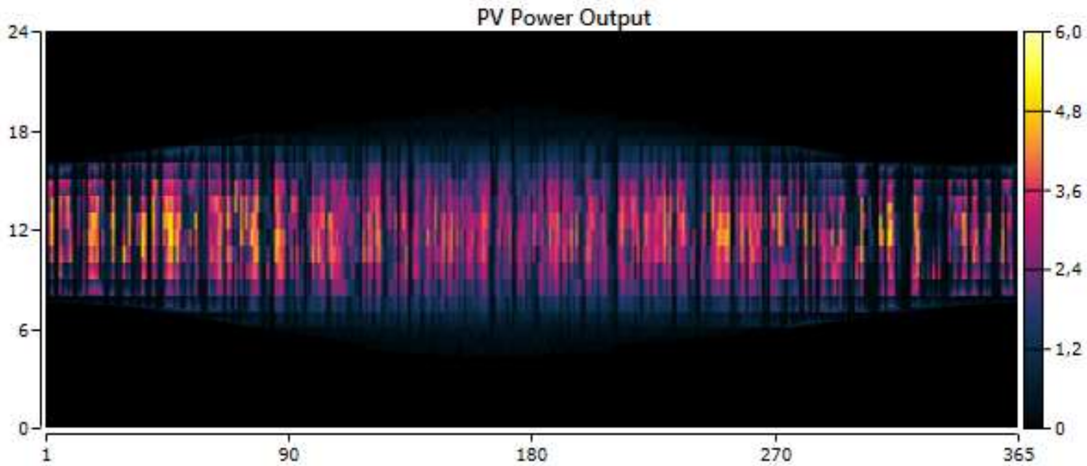

Figure 7.46. *PV power output per day and hour.*

The performance data of the batteries is detailed here in Table 7.29.

Table 7.29. *Functioning data of the batteries.*

String size	1 battery
Strings in parallel	6 strings
Energy in	2,624 *kWh*/year
Energy out	2,389 *kWh*/year
Storage depletion	57.3 *kWh*/year
Losses	292 *kWh*/year
Annual throughput	2,533 *kWh*/year
Autonomy	169 hours
Storage wear cost	0.102 €/*kWh*
Nominal capacity	79.2 *kWh*
Usable nominal capacity	79.2 *kWh*
Lifetime throughput	25,329 *kWh*
Expected life	10 years

The state of charge of the batteries is presented in Figure 7.47.

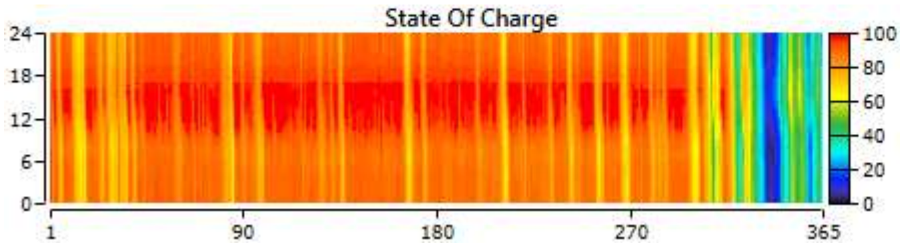

Figure 7.47. *State of charge of the batteries per day and hour.*

The inverter performance data is detailed in the Table 7.30 and we can see also the inverter output in Figure 7.48.

Table 7.30. *Functioning of the inverter.*

Rectifier capacity	2.40 *kW*
Inverter capacity	3 *kW*
Mean output	0.470 *kW*
Maximum output	2.39 *kW*
Capacity factor	15.7 %
Hours of operation	8,760 hours
Energy out	4,114 *kWh*/year
Energy in	4,285 *kWh*/year
Losses	171 *kWh*/year

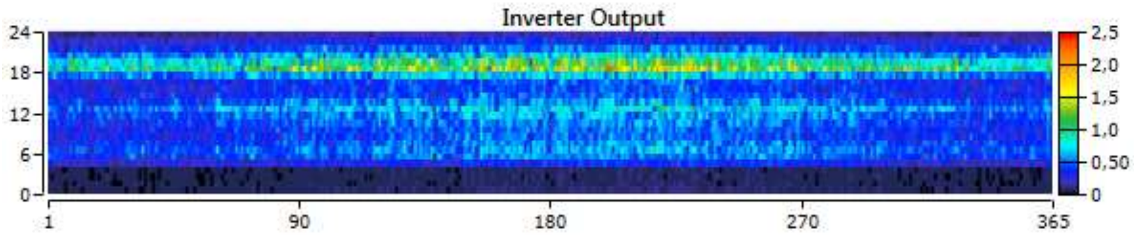

Figure 7.48. *Inverter output per day and hour.*

7. Conclusions

After seeing the results from all the simulations in HOMER using all the different types of equipment for our microgrids, we can conclude that an isolated microgrid is less profitable economically nowadays than an on-grid microgrid. This on-grid case is using the PV panels to reduce the amount of energy purchased from the grid during the day and, in addition, is selling back some of the electricity produced to the utility generating profits.

In the case of stand-alone microgrids, nowadays is still more economically viable to purchase the energy directly from the grid instead of spending all this money in the installation and usage of the microgrid, although it is more sustainable and beneficial for the environment and the planet.

The cheaper equipment is more profitable economically although is less efficient in electricity production. The more expensive microgrid on-grid system equipment has a cheaper cost of electricity than the market price in Croatia, which is called grid-parity, while the cheaper equipment almost reached that price from the expensive equipment. Anyway, the difference is contemptible, and having into account the differences between the initial investment and the operation and maintenance costs, we can say that if we have a microgrid connected to the utility, it's advisable not to spend too much in the most expensive equipment, as the cheapest one can meet the expectations as well.

The large amount of energy sold to the grid is due to the high price of selling back electricity for prosumers in Croatia; however, not in all the countries the law is so benevolent with the microgrid users, and the economic viability can vary depending on the regulation in force at the moment.

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Abstract:

In this paper, we have carried out the electrical performance and the cost-benefit analysis of a domestic microgrid based on renewable energy sources. The software used in this work in order to perform the simulations is Homer Pro, which enabled modelling of microgrid and all its parameters in a period of one year, accounting the real weather conditions and usage hours of the electric loads of the building we are working with. The microgrid consists of polycrystalline photovoltaic panels, a set of batteries, the utility (depending on the case study), and the load, which represents a prototype house and an inverter and controller that allow us to manage the energy flows between all the elements of the microgrid. Two case studies were conducted; in first, our microgrid was isolated from the electrical network and in the other, we counted on its support.

Keywords: *microgrid, PV, batteries, cost-benefit analysis, electrical performance analysis.*

Curriculum Vitae

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	Listening	Reading	Spoken interaction	Spoken production	
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	Cambridge English: First Certificate				

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Common European Framework of Reference for Languages

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Proficient user	Independent user	Independent user	Independent user	Independent user

Digital skills - Self-assessment grid

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